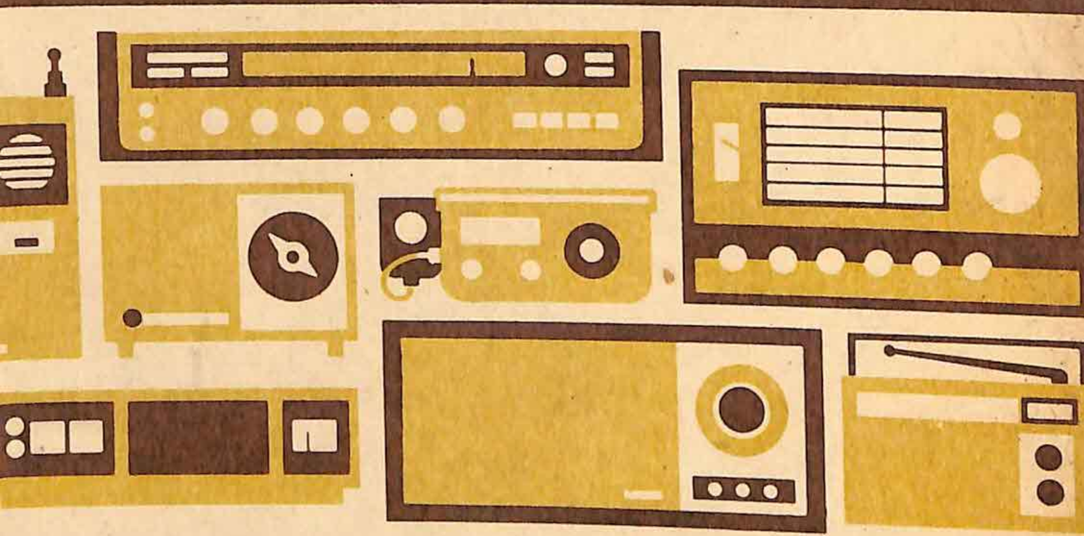
BASIC RADIO

REVISED EDITION

VOLUME 6



MARVIN TEPPER

TRANSMITTERS

TRANSMITTING TUBES
OSCILLATORS
CRYSTALS
AMPLIFIERS
FREQUENCY MULTIPLIERS
AMPLITUDE MODULATION
FREQUENCY MODULATION
POWER SUPPLIES
TRANSMISSION LINES
RADIATION
ANTENNAS

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vol. 6

REVISED EDITION

MARVIN TEPPER

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PREFACE

Basic Radio is a course in communications electronics, as distinct from a general course in electronics. The text deals with the circuitry and techniques used for the transmission and reception of intelligence via radio energy. Assuming no prior knowledge of electricity or electronics, the six volumes of this course "begin at the beginning" and carry the reader in logical steps through the study of electricity and electronics required for a clear understanding of radio receivers and transmitters. Illustrations are used profusely to reinforce the highlights of the text. All examples given are based on actual or typical circuitry to make the course as practical and realistic as possible. Most important, the text provides a solid foundation upon which the reader can build his further, more advanced knowledge.

No prior knowledge of electricity or electronics is required for the understanding of this series. Because this series embraces a vast amount of information, it cannot be read like a novel, skimming through for the high points. Each topic contains a carefully selected thought or group of thoughts, so that each unit can be studied as a separate subject. Mathematics is kept to a minimum and, where necessary, the mathematical methods are fully explained.

This Revised Edition of *Basic Radio* retains the structure of the First Edition. Volume 1 treats d-c electricity. The slightly more involved subject of a-c electricity is presented in Volume 2. Equipped with this information, the reader is ready to study the operation of electron tubes and electron tube circuits in Volume 3, including power supplies, amplifiers, oscillators, etc. The components of electronic circuitry presented in Volumes 1 through 3 are assembled in Volume 4, which discusses the complete radio receiver, AM and FM. Volume 5 gives special attention to the theory and circuitry of transistors and integrated circuits. Volume 6 covers the long-neglected subject of transmitters, antennas, and transmission lines. In sum, the full range of the fundamentals of communications electronics is covered in a manner that provides maximum comprehension with a minimum of effort.

To the many people whose thoughts and discussions have contributed to this series, my sincere appreciation. To my wife, Celia, and my daughters, Ruth and Shirley, with whom I would have preferred to spend more time, my heartfelt thanks and gratitude for their assistance and understanding patience.

MARVIN TEPPER

Falmouth, Massachusetts

CONTENTS

vol. 6

INTRODUCTION TO TRANSMITTERS 1

Communication by Radio • Kinds of Radio Signals • The Basic Radio Transmitter (Radiotelegraphy)

TRANSMITTING TUBES 4

Transmitting Tubes: The Emitter; Grids; The Plate • External Anode — Ceramic Tubes • Transmitting Tube Ratings • Transmitting-Type Rectifiers (Organization of Gaseous Tubes) • Transmitting-Type Gaseous Rectifiers (Theory)

TRANSMITTER OSCILLATORS 11

The Oscillator • Oscillator Losses • Oscillator Characteristics • Hartley Oscillator • Colpitts and Clapp Oscillators • Transistor Oscillators • The Tuned-Plate Tuned-Grid Oscillator

CRYSTAL CHARACTERISTICS 19

Action of Crystals • Crystal Cuts • Temperature Coefficient • Oscillator Harmonics • Crystal Holders • Crystal Characteristics

CRYSTAL OSCILLATORS 25

Basic Crystal Oscillator • Pierce Oscillator • The Crystal-Overtone Oscillator

SPECIAL OSCILLATOR CONSIDERATIONS 28

The Variable-Frequency Oscillator (VFO) • Oscillator Coupling and Loading

Summary and Review Questions 30

CLASS-C AMPLIFIERS 31

The Class-C Amplifier • The Class-C Tuned R-F Amplifier • Class-C Amplifiers — The Plate Circuit • Transistor Class-C Amplifiers

FREQUENCY MULTIPLIERS 37

Buffer Amplifiers • Frequency Multipliers • Frequency-Multiplier Amplifiers • Diode Harmonic Generator • Tuning Frequency Multipliers

INTERSTAGE COUPLING 43

Interstage Coupling

R-F POWER AMPLIFIERS 45

The Tuned R-F Amplifier and Driver Stage • The Tuned R-F Power Amplifier • Neutralization • Transistor R-F Amplifier Neutralization • Power-Amplifier Input Circuits • Input Circuits for Push-Pull Amplifiers • Single-Ended Power Amplifiers • Push-Pull Power Amplifiers • Power-Amplifier Output Circuits • Output Coupling • Bias Voltages • Transmitter Meters • Output and Input Power • Tuning Procedure

TRANSMITTER KEYING 63

Keying

CW TRANSMITTER 67

Basic CW Transmitter

Summary and Review Questions 68

AMPLITUDE MODULATION 69

AM Transmission • Percentage of Modulation • Sidebands • Power Distribution in an AM Wave

THE AM TRANSMITTER 74

The Basic Amplitude-Modulated Transmitter • Modulation Levels • Heising Modulation • Transformer Coupling (Plate Modulation) • Control-Grid Modulation • Screen-Grid Modulation • Modulation Checking

MICROPHONES 82

Microphones – Carbon and Crystal; Dynamic and Ribbon

MODULATOR CIRCUITS 84

Speech Amplifiers • Modulator Driver • Modulator Stages • Speech Clipping and Limiting • Automatic Limit Control (ALC)

CW-AM TRANSMITTER 92

Basic CW-AM Transmitter

Summary and Review Questions 93

FREQUENCY MODULATION 94

Direct FM • Indirect FM • The Armstrong Phase-Modulation Circuit • Phase Modulation (PM)

SINGLE-SIDEBAND TRANSMISSION 99

Basics of Single-Sideband Transmission • Carrier Suppression by Balanced Modulators • Carrier Suppression by Balanced-Bridge Modulators • Sideband Suppression: Bandpass Filters • Crystal Filters • Phasing Method • Linear Amplifiers • Basic SSB Transmitters

POWER SUPPLIES AND CONTROLS 108

Transmitter Power Supplies • D-C to D-C Converter Power Supply • Transmitter Controls • Transmitter Control System • Transceiver

Summary and Review Questions 117

TRANSMISSION LINES 118

Transmission Lines • Types of Transmission Lines • Inductance and Capacitance in Transmission Lines • Characteristic Impedance of an Infinitely-Long Transmission Line • Terminating the Transmission Line • The R-F Transmission Line Transports Electromagnetic Energy • Electrical Wavelength • Electrical Wavelength and Velocity of Propagation • Transmission Lines Terminated in Characteristic Impedance • Transmission Line Not Terminated in Characteristic Impedance • Resonant Transmission Lines (Open Circuited) • Resonant Transmission Lines (Short-Circuited) • Properties of Transmission-Line Sections • Typical Applications of Transmission-Line Sections

WAVE PROPAGATION 132

Radiation • Electric and Magnetic Fields in Free Space • The Free-Space Wave (Velocity, Frequency, Wavelength) • The Wavefront • Practical Wave Propagation • Ground, Ground-Reflected, and Direct Waves • Line-of-Sight Propagation: Temperature Inversion • Sky-Wave Propagation (The Ionosphere) • Angle of Radiation and Skip Distance

ANTENNA CHARACTERISTICS 141

The Fundamental Antenna • The Half-Wavelength Dimension • Resonance in the Half-Wave Dipole • Voltage and Current in the Half-Wave Dipole • Antenna Impedance • Antenna Input Impedance and Radiation Resistance • Directivity of Resonant Half-Wave Dipole

ANTENNAS 148

Parasitic Arrays (Yagi Antennas) • Operation and Characteristics of the Parasitic Array • The Folded Dipole • The Vertical Antenna • The Long-Wire Antenna • The V Antenna • The Rhombic Antenna • Feeding the Antenna (SWR)

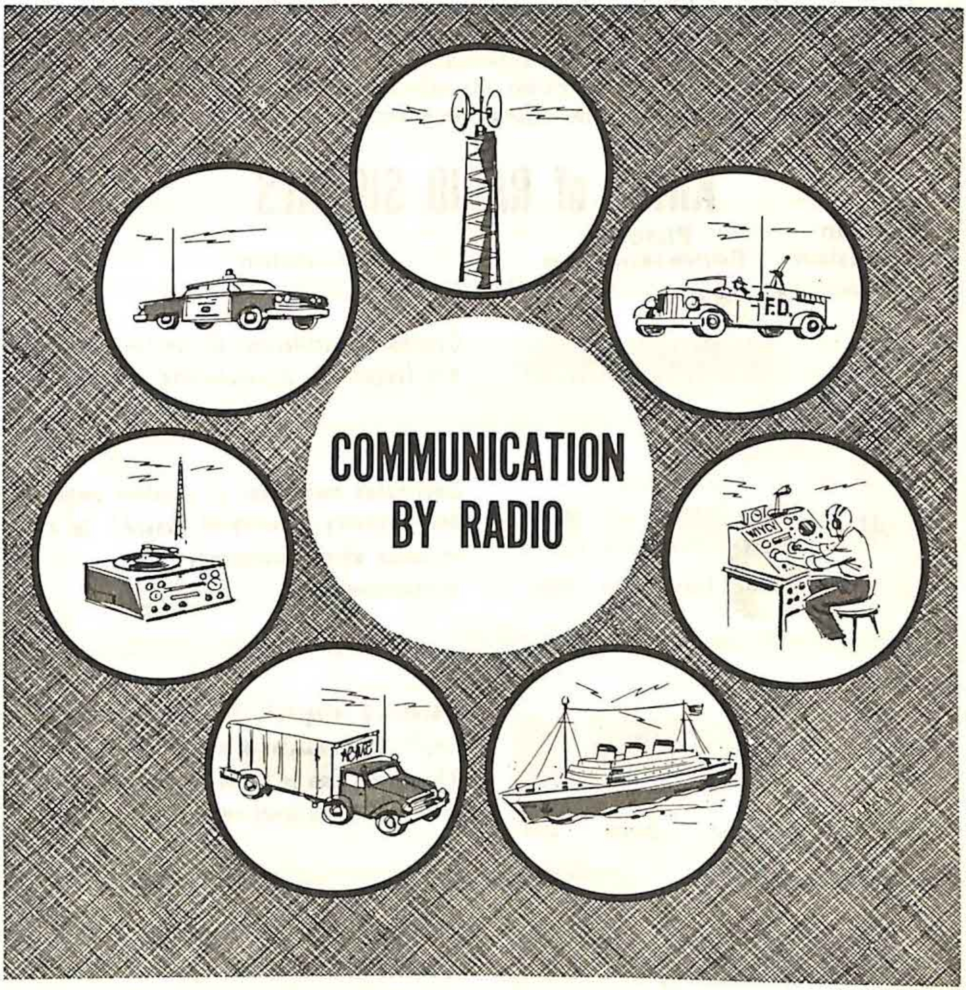
Summary and Review Questions 157

GLOSSARY 158

INDEX 160

CUMULATIVE INDEX 165

Communication by Radio

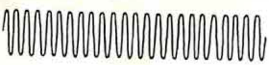
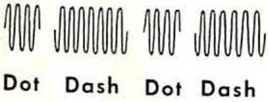
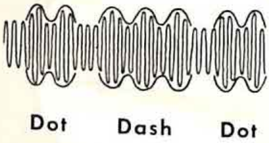
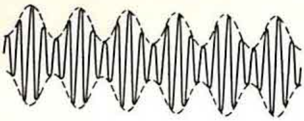


In the broadest sense, "communication by radio" means the transfer of intelligence from one point to another through space, using radiated electromagnetic energy (radio waves) in the frequency spectrum of from about 10 kHz to about 30,000 MHz. The transmitting antenna radiates these waves and the receiving antenna intercepts them. This extremely broad span of frequencies embraces many different techniques which come within the meaning of radio communications. In some of them the nature of the intelligence transmitted differs greatly from that dealt with in this book. But even so, there are many similarities in the organization and operation of the different transmitters used in the various radio services. Understanding the theory of operation of the conventional radio transmitter will help in comprehending the functioning of all other kinds of transmitters.

Kinds of Radio Signals

We have already established that communication by radio is accomplished by electromagnetic energy (electromagnetic waves) which travel from a transmitting antenna to the receiving antenna. This broad statement does not, however, identify the kinds of radio signals that come within the boundaries of electromagnetic waves. The differences among radio signals arise principally from the techniques employed in making the intelligence part of the radiated signal prior to radiation.

KINDS of RADIO SIGNALS

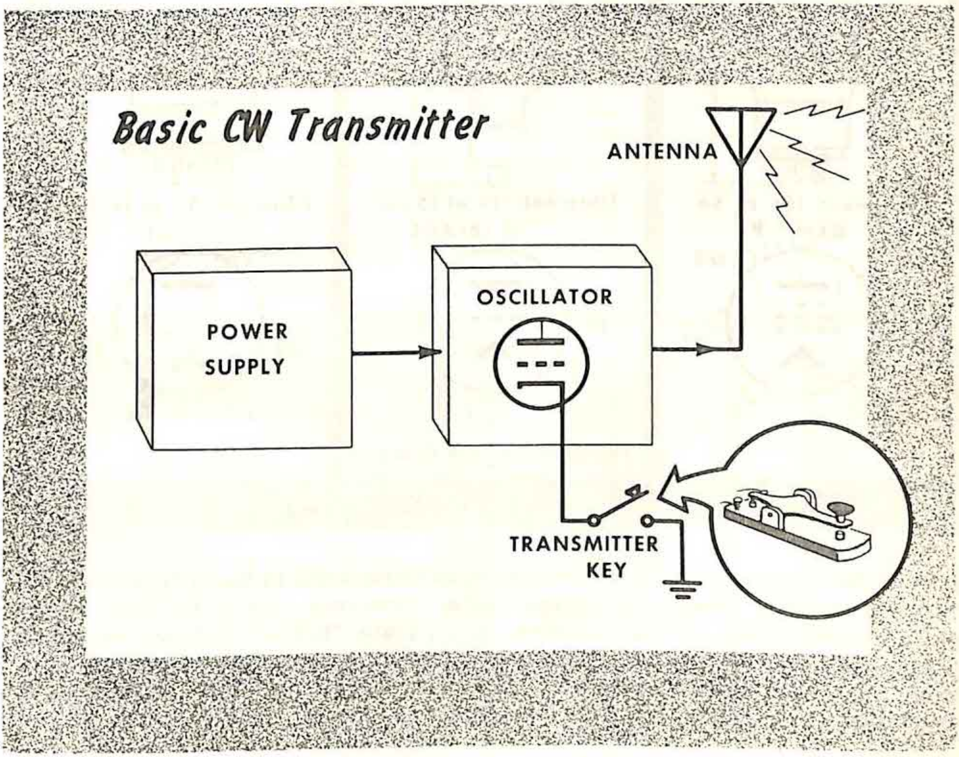
Emission Designation	Pictorial Representation	Description
A0		Continuous oscillations of constant amplitude and frequency. Nonmodulated waves.
A1		Continuous oscillations of constant amplitude and frequency, interrupted (keyed) in a sequence which corresponds to an International code.
A2		Modulated telegraphy in which an audio tone amplitude modulates a carrier. The audio tone is keyed in accordance with an International code.
A3		Telephony. Constant-frequency oscillations modulated by the intelligence being transmitted.

These differences give rise to different identifications. The identity of each type of radio signal is called a type of emission. Modern communication technology has given rise to a great many kinds of modulation; hence, kinds of emission. This being a course in basic radio, only the broadly applicable techniques are discussed. Where variations warrant mention, they are dealt with separately.

The Basic Radio Transmitter (Radiotelegraphy)

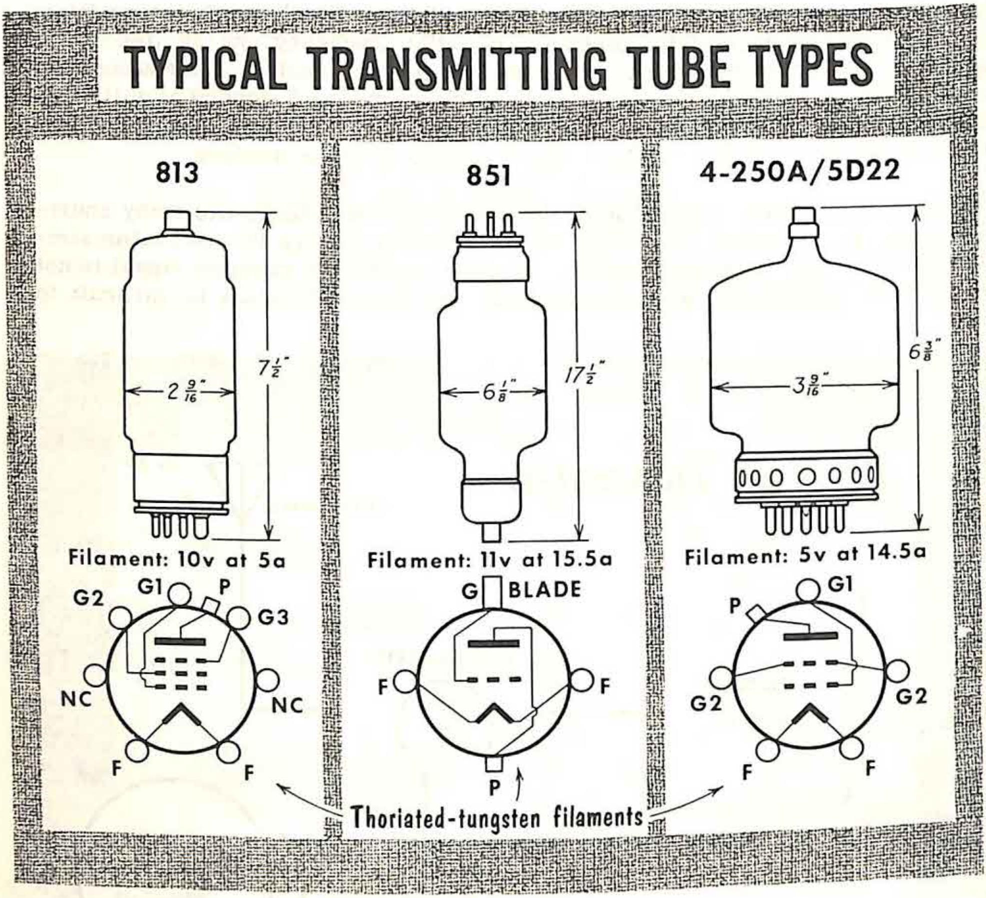
The most fundamental radio transmitter is the radiotelegraph transmitter. It consists of a vacuum-tube generator of radio-frequency energy (the oscillator); a source of operating voltages (the power supply); a signaling key whereby the generation of oscillations can be started and stopped at will, and an antenna. In the strict sense the antenna is not part of the transmitter, but it is a necessary adjunct, without which a transmitter is useless.

The basic transmitter made up of the abovementioned parts has many shortcomings. Its greatest deficiency is its inability to keep the oscillator constant on a precise frequency setting; in other words, the radiated signal is not constant in frequency, and consequently the received signal is difficult to "read." Also, the signal power derived from the oscillator is low, which limits the distance over which communications can be carried on.



Manipulating the signaling key to close and open the circuit in accordance with the radiotelegraphy code causes the oscillator to generate corresponding bursts of energy. This energy radiates from the antenna to "transmit" the message. Transmitters used for radiotelegraph purposes are called continuous wave or CW transmitters.

Transmitting Tubes: The Emitter


TYPICAL TRANSMITTING TUBE TYPES

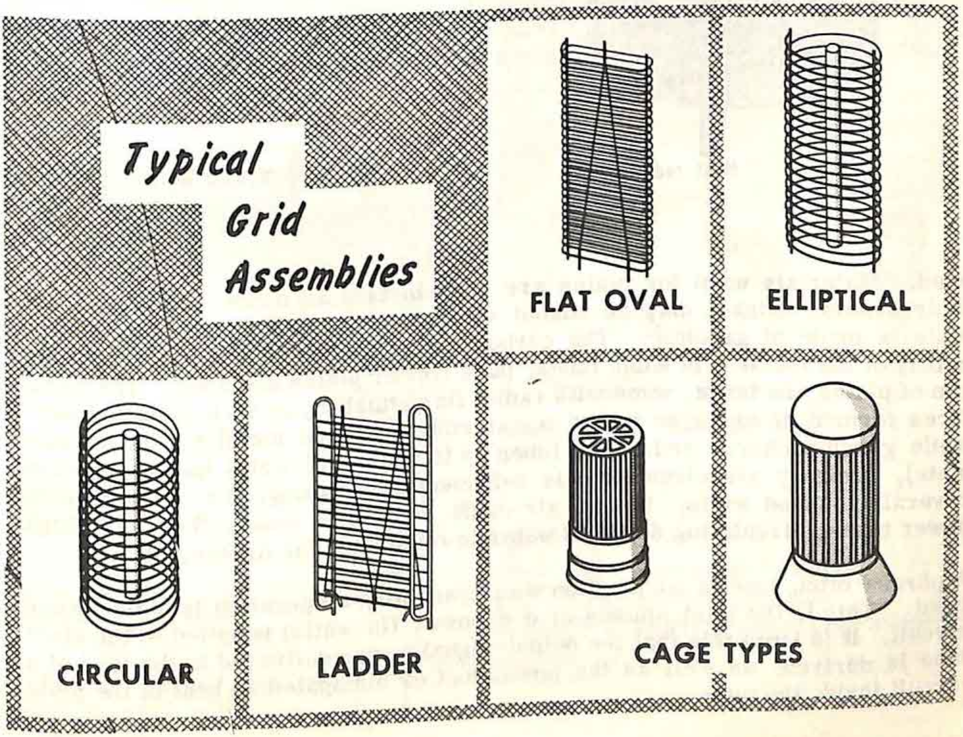
Many of the tubes used in radio receivers are also used in radio transmitters. This is especially true in low-power units. However, due to the many high-power circuits used in transmitters, a separate "breed" of tubes known as transmitting types are used. Generally, they are of special construction to handle the larger amounts of power. They are larger, specially shaped, have rugged plate, grid, and filament elements, and special basing arrangements.

The high plate current generally found in transmitting tubes necessitates the use of emitters rich in sources of electrons. Both indirectly-heated cathodes, and directly-heated filaments are used. The cathode emitters are barium-oxide or strontium-oxide coated surfaces, brought to electron-emitting temperature by an associated heater. Directly-heated filaments are made of tungsten, with thorium oxide impregnated in the metal during manufacture, or nickel, coated with an emitting material. The thoriated-tungsten filament is extremely popular, but must be operated within 5% of its specified voltage rating. For this reason, many transmitters have a "filament voltage" meter and adjustment to permit monitoring of this voltage.

Transmitting Tubes: Grids

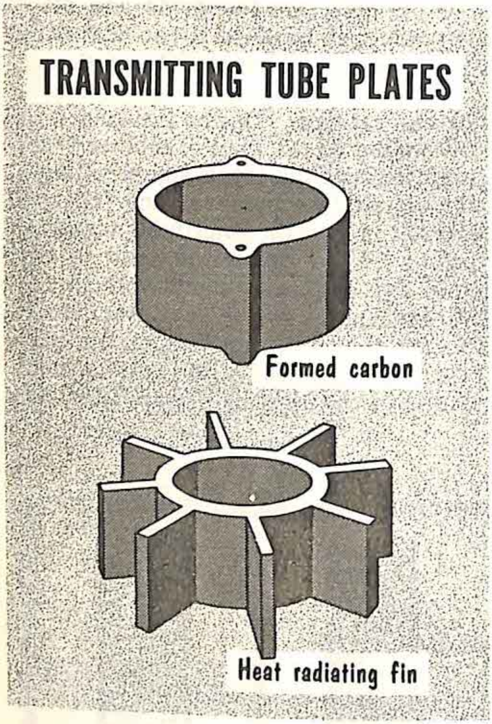
The control grid in a transmitting-tube type resembles its receiving tube counterpart – a spiral form, or ladder structure. In some tubes the control grid is a cage-like structure that surrounds the emitter. Materials used for grids include pure metals such as tungsten, molybdenum, or tantalum, or various alloys of these metals. With the grids located between heat radiators such as the filament and plate, they may emit primary electrons when bombarded by ions from gas in the tube. To prevent this the grids are often coated with gold or platinum. Platinum is preferred because it can withstand higher temperatures without vaporizing. Carbon is also commonly used.

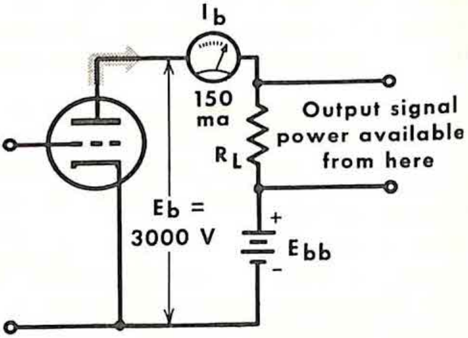
Control-grid electrodes are subject to several ratings. One is the grid-bias voltage, which may be negative or zero, depending on the kind of tube and how it is used. Another is the safe peak amplitude of the input-signal voltage. Excessive input-signal voltage can not only impair tube performance, but can damage the tube. Another rating encountered in certain amplifying applications in transmitters is called driving power or r-f excitation, and is expressed in watts. If the application demands that the input-signal voltage exceed the applied negative grid bias, a unidirectional or d-c grid current flows between the emitter and the control grid inside the tube, and around the control grid – emitter circuit outside the tube. The product of the grid current and the peak positive grid – emitter voltage is the driving power (in watts) that is consumed in the grid circuit.



Transmitting Tubes: The Plate

The plate or anode of a transmitting tube is the point of greatest difference between receiving and transmitting tubes. In transmitting tubes the plate is subjected to tremendous impact by tube current, and accounts for much of the heat produced in the tube. To withstand high temperatures, the plate must radiate the heat, and a variety of materials and constructional features are used. Materials used for plates are such metals as nickel, tantalum, and molybdenum. Nickel may be coated with carbon, and sometimes the entire plate is made of graphite. The carbonized coating aids the heat-radiating ability of the metal. In some tubes, pure copper plates are used. The usual run of plates are large, some with radial fins attached, or with radiating surfaces formed of edgewise wound metal ribbon. Often metal plates operate while glowing cherry red. For tubes up to about 250 watts (power input to plate), ordinary air circulation is sufficient for cooling; for ratings up to several thousand watts, forced air-draft cooling is used. For very high power tubes, circulating distilled water is often used for drawing off heat.





Total Plate Power Input

= D-c plate voltage × d-c plate current

$$= E_b \times I_b$$

$$= 3000 \times 0.150$$

$$\boxed{= 450 \text{ watts}}$$

A phrase often used in conjunction with transmitter operation is plate-power input. This is the total amount of d-c power (in watts) supplied to the plate circuit. It is from this that the output-signal power delivered to the load of a tube is derived, as well as the power lost or dissipated as heat in the plate circuit inside the tube.

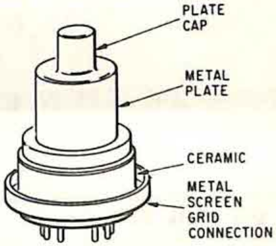
External Anode—Ceramic Tubes

One of the drawbacks noted in transmitting tube operation was the need for dissipating large quantities of heat developed in the plate. Another drawback is the difficulty in providing efficient coupling of the resonant circuit to the plate cap. This is particularly critical in frequencies above 50 MHz. To overcome these problems, tube manufacturers developed transmitting tubes in which the anode is a circular metal plate that is part of the external tube housing. To aid in heat dissipation, the circular metal plate is vacuum sealed to a ceramic base containing the control grid, screen grid, cathode, and filament. Ceramic, capable of withstanding high temperatures, allows using the tube at higher frequencies where the r-f field would overheat glass, causing glass tube failures.

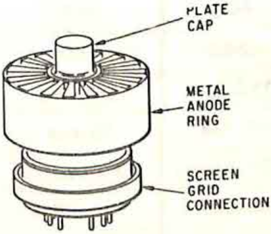
The tubes have in addition to a pin connection a metal ring just above the base that can also be used for the screen grid connection. Although the tubes have a conventional plate cap, the circular plate and screen grid connection placement permits using the tube in a coaxial arrangement for high frequency operation.

For higher power, a similar tube using heat radiating fins attached to the anode is illustrated. A metal ring surrounding the fins is used as the anode connection. A similar version of external anode ceramic tube designed exclusively for high frequencies is illustrated showing all the internal elements brought out to circular rings. In use these tubes require special concentric sockets designed for high frequency operation. The construction of these high frequency tubes using concentric rings also includes specially designed internal grid "cups" in which the grids are shaped and aligned in one operation to improve performance.

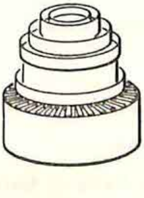
TYPICAL EXTERNAL ANODE TUBES



Metal Anode—Ceramic Tube



Addition of Fins for Added Anode Heat Dissipation



Coaxial Metal Anode Ceramic Tube for High Frequency Operation

Transmitting-Tube Ratings (CCS, ICAS, and Typical Operation)

Exclusive of the filament or heater voltage and current, both of which are fixed for any given tube regardless of use, the safe maximum operating voltages applied to the control grid, screen grid (where applicable), and the plate electrodes, as well as the safe maximum amounts of current permitted to flow in these circuits, are determined by two standard conditions of use of the tube. They are called CCS ratings and ICAS ratings. Both are usable for guidance. The letters CCS stand for Continuous Commercial Service, which means continuous, around-the-clock operation consistent with maximum tube life and dependability. In contrast, is the ICAS rating. These letters stand for Intermittent Commercial and Amateur Service, by which is meant alternate periods of "on" and "off" operation, each theoretically lasting for five minutes. In practice, time is disregarded during the "on"-"off" periods. The philosophy behind the ICAS rating is highest signal output from the tube with only limited concern for long tube life.

In addition to the CCS and ICAS ratings of safe maximum values of voltage and current, there is always still another set of operating conditions known as typical operation. The typical operating values can conform with CCS operation or with ICAS operation, depending upon the circumstances. But whichever it is, the typical operating voltage and currents are in almost all instances below the CCS or the ICAS ratings. We show, for comparative purposes, CCS and ICAS ratings, and typical operating conditions for a standard transmitting tube. Those tubes not intended for ICAS service bear only CCS and typical operating specifications.

EXAMPLES of MAXIMUM CCS and ICAS RATINGS and TYPICAL OPERATION of 814 TUBE used as R-F POWER AMPLIFIER

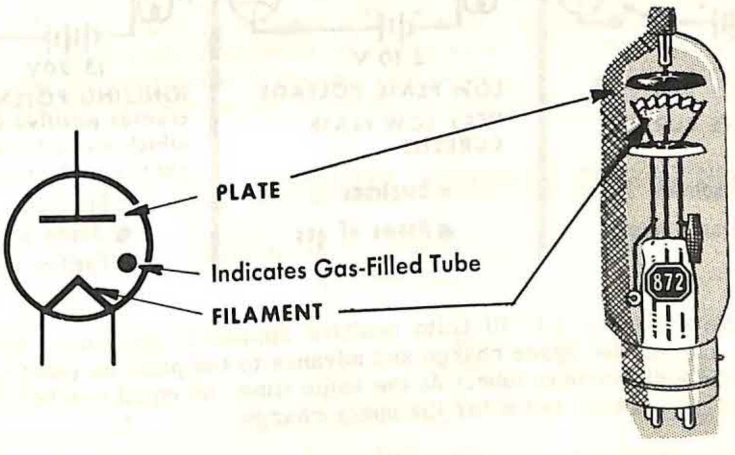
	Maximum		Typical Operation
	CCS	ICAS	
D-c Plate Voltage	1250	1500	1250
D-c Screen-Grid Voltage	400	400	300
D-c Control-Grid Voltage	-300	-300	-80
D-c Plate Current	150 ma	150 ma	144 ma
D-c Control-Grid Current	15 ma	15 ma	10 ma
Plate Input	180 watts	250 watts	180 watts
Screen-Grid Input	10 watts	10 watts	10 watts
Plate Dissipation	50 watts	65 watts	45 watts
Driving-Power Control Grid	1.5 watts	1.5 watts	1.5 watts

Transmitting-Type Rectifiers (Organization of Gaseous Tubes)

The gas-filled or gaseous rectifier is a two-element tube (diode) consisting of an indirectly-heated cathode, or a filament and a plate (anode) in a glass envelope. Also within the envelope is a small amount of gas such as argon, neon or xenon among others, or a small amount of liquid mercury. The rectifier that uses the liquid mercury is known as a mercury-vapor tube because the liquid mercury vaporizes when the hot emitter raises the temperature of the envelope sufficiently. The xenon-filled, and the mercury-vapor diodes are standard half-wave rectifiers.

Gaseous rectifiers are used in transmitter power supplies when the d-c voltage required is at least 1000 volts, and the current requirement is at least 150 milliamperes dc. They are used in rectifying circuits similar to those

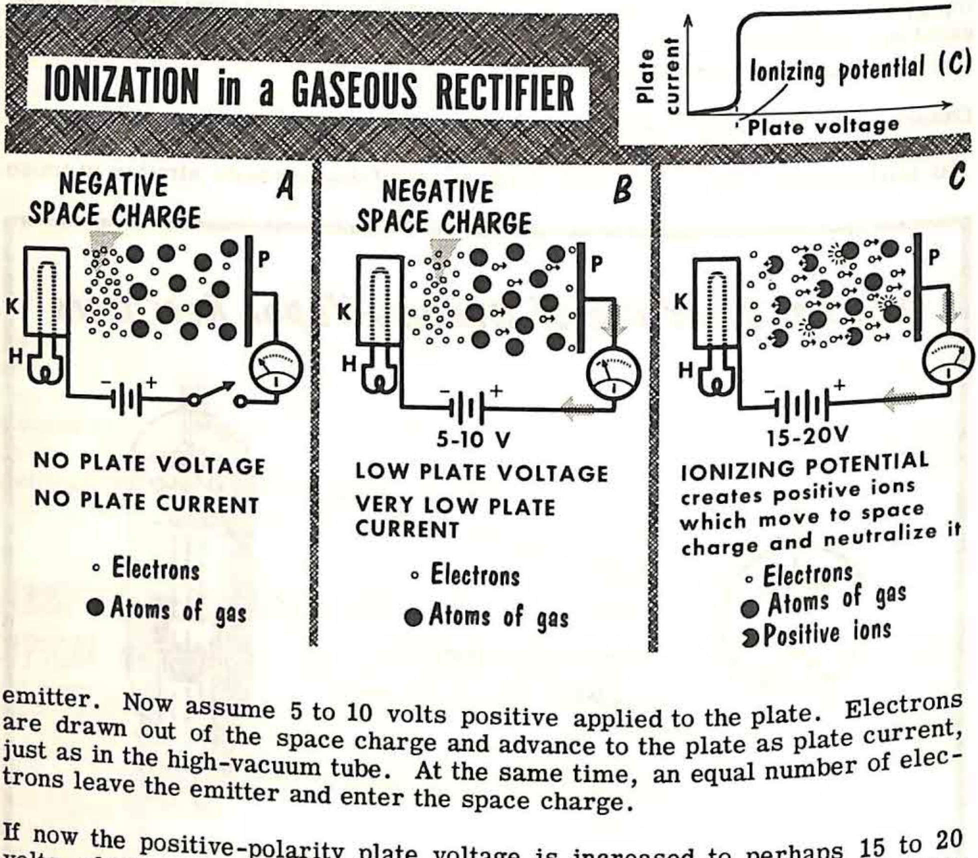
Internal Structure of Mercury-Vapor Rectifiers



used with high-vacuum tubes, namely, half-wave, full-wave, and bridge arrangements. Because of the manner of functioning, the gas-filled rectifier does not permit the simultaneous "on" and "off" application of the heater and plate voltages. When the tube is placed into service for an operating period, the heater voltage must be applied first, without application of the plate voltage, for at least 30 seconds. Then the plate voltage is applied. The time interval stated is necessary to allow the tube to heat sufficiently, and especially to allow the mercury to vaporize. Once the emitter has reached the proper temperature, the plate voltage can be applied or removed at will. The heater voltage must remain on all the time the power supply is in service, even though the plate voltage is not applied.

Transmitting-Type Gaseous Rectifiers (Theory)

Assume a half-wave gaseous rectifier with the hot cathode emitting electrons, and no voltage on the plate. The gas or the mercury vapor content of the tube corresponds to a cloud of atoms of the substance dispersed throughout the tube. The electrons from the cathode form a space charge around the emitter. Now assume 5 to 10 volts positive applied to the plate. Electrons are drawn out of the space charge and advance to the plate as plate current, just as in the high-vacuum tube. At the same time, an equal number of electrons leave the emitter and enter the space charge.



If now the positive-polarity plate voltage is increased to perhaps 15 to 20 volts, electrons drawn out of the space charge have a higher velocity, collide with the atoms of gas, and knock electrons out of the atoms, thus making them positive ions. The voltage at which the electrically neutral atoms are changed to positive ions is called the ionizing potential. The positive ions are repelled by the positively-charged plate and are attracted to the space charge which, consisting of electrons, is the equivalent of a negatively-charged cloud. When the positive ions enter the space charge, the space-charge electrons are attracted to the positive ions, thus making the latter electrically neutral, and neutralizing the space charge. In effect, there is no space charge. Now all the emitted electrons move to the plate as plate current. If the positive-plate voltage falls below the ionizing potential, de-ionization of the gas occurs and space charge reappears. Gaseous rectifiers have exceptionally low internal plate resistance. This makes them useful for high current rectifiers.

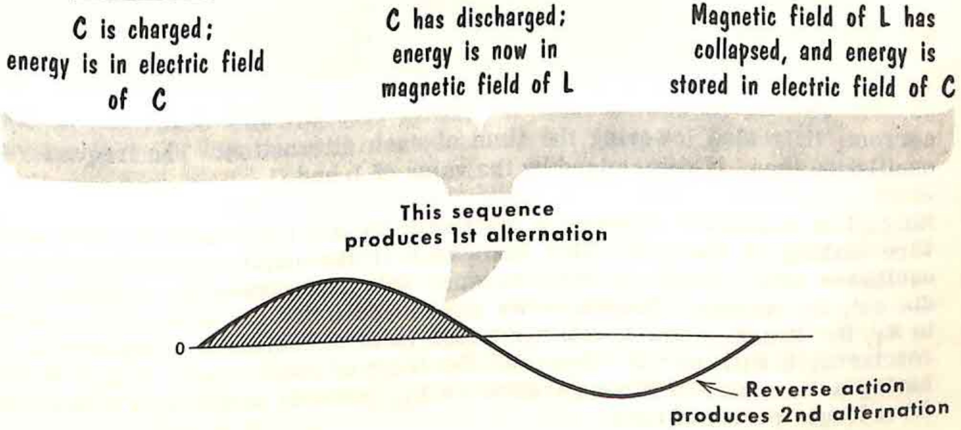
The Oscillator

Oscillators are the heart of a transmitter, often the transmitter itself. It would be best to begin by a review of the basics of oscillator circuits. An inductance and a capacitance is the basis of an oscillatory circuit. Assuming C to be fully charged, it will discharge, building a magnetic field about L. When C is fully discharged the energy of the circuit is in the magnetic field about L. With C discharged there is no longer any difference of potential to keep the current flowing through the circuit. The field about L collapses, inducing a back EMF. The induced back EMF causes the current to again flow in the original direction. The collapsing field then recharges C, but in the opposite polarity to that with which it was originally charged.

When the field about L has completely collapsed, all the energy of the circuit is once again stored in C. The capacitor again discharges. The action of building a field about L is repeated, as is the collapsing field that again charges C. The polarity of the charge on C now is the same as that with which it started, completing the cycle.

Plotting the capacitor current flow from the initial point where no current is flowing, through the point where maximum current is flowing as C discharges, back to the point where no current is flowing as C is recharged in the opposite polarity, provides one alternation of a sine wave. When the cycle is repeated, it provides an alternation in the opposite polarity. Combining the two alternations results in a sine wave of current flowing in the circuit.

OSCILLATORY DISCHARGE PRODUCES SINE WAVE



C is charged; energy is in electric field of C

C has discharged; energy is now in magnetic field of L

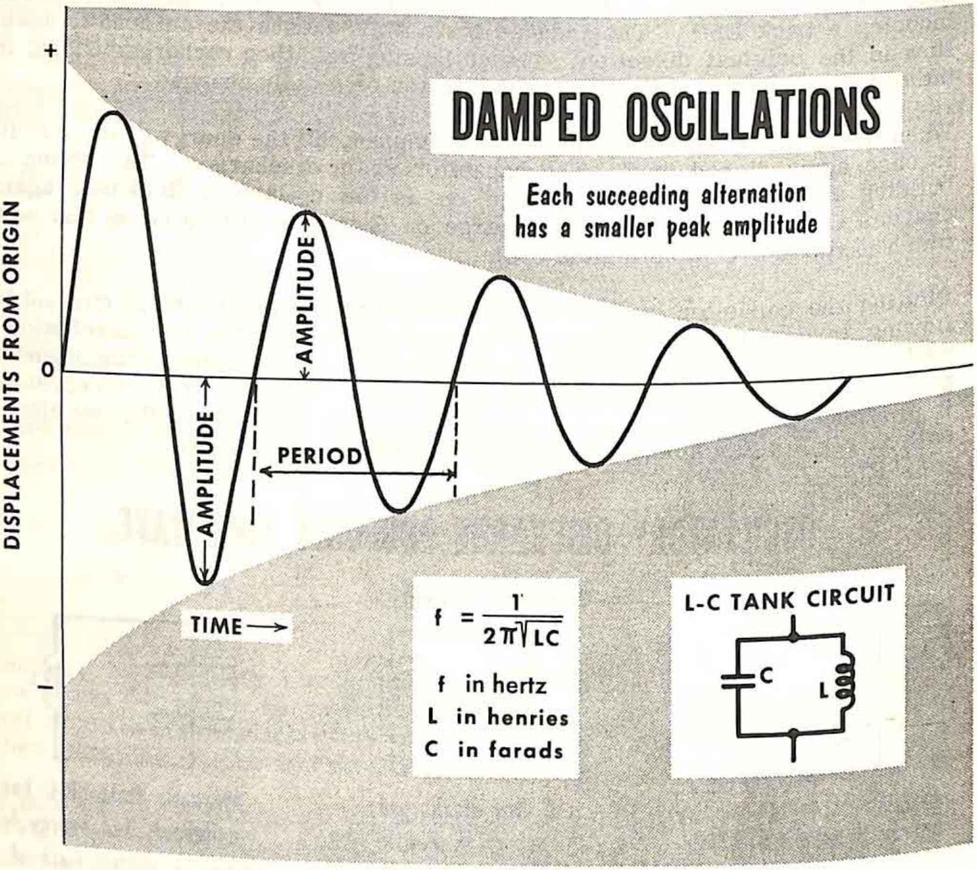
Magnetic field of L has collapsed, and energy is stored in electric field of C

This sequence produces 1st alternation

Reverse action produces 2nd alternation

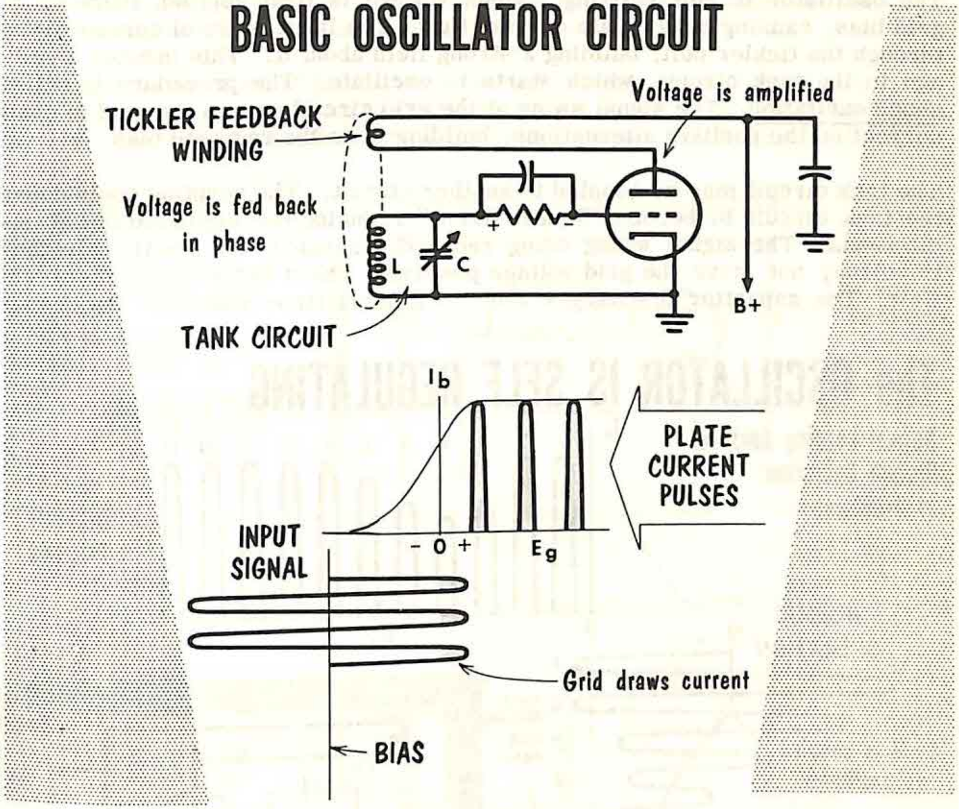
Oscillator Losses

Assuming perfect capacitor and inductors, there would be no loss in an L-C circuit, or "tank" circuit; the oscillations would continue indefinitely. The frequency of the oscillations is dependent upon the values of L and C. A large value C takes more time to charge and discharge, producing a low frequency. A large value of inductance offers greater impedance to the flow of current, thus also lowering the time of each alternation. The frequency of oscillation then, is determined by the value of L and C.


DAMPED OSCILLATIONS
Each succeeding alternation has a smaller peak amplitude
DISPLACEMENTS FROM ORIGIN
+
0
–
AMPLITUDE
AMPLITUDE
PERIOD
TIME →
$f = \frac{1}{2\pi\sqrt{LC}}$
f in hertz
L in henries
C in farads
L-C TANK CIRCUIT
C
L

No coil is a perfect inductor; it must have the d-c resistance of the turns of wire making up the coil. This resistance is the major source of loss in an oscillator tank circuit. If not overcome, this loss causes the oscillations to die out, or become "damped." We have learned that the Q of a coil is equal to X_L/R. Hence, a low-Q coil has a high value of resistance compared to its reactance; it will quickly "dampen" the train of oscillations. A high-Q coil having a low value of R compared to its X_L, permits oscillations to continue for a longer period of time.

Oscillator Losses (Cont'd)



To maintain constant amplitude of the oscillations in the tank circuit the damping effect of the resistance of the coil must be overcome. Applying the oscillations of the tank circuit to the grid of a vacuum-tube amplifier makes available at the plate circuit an increased amount of power at the same frequency as that of the tank circuit. A controlled amount of energy from the amplified output is fed back to the tank circuit. This energy is fed back in phase, called regenerative feedback. The output of the plate circuit being 180° out of phase with the grid circuit, it must be shifted another 180° to place it in phase with the grid circuit.

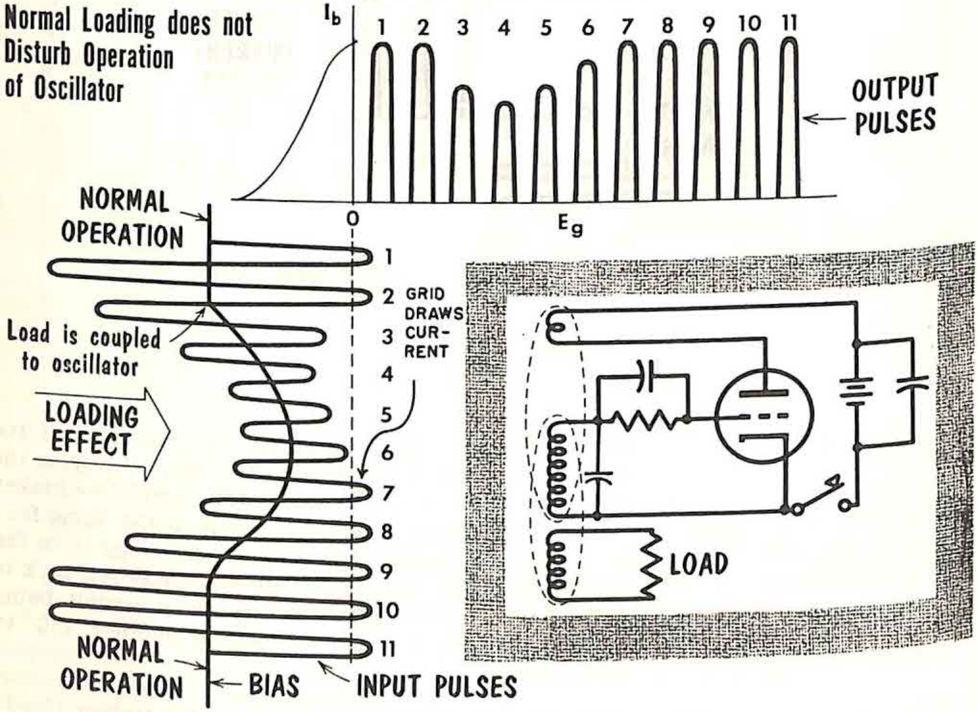
The output plate current signal is inductively coupled from the tickler (feedback) coil to the tank circuit, in phase, to maintain oscillations in the tank circuit. If the feedback of the tickler coil is not in phase, the circuit will not oscillate. The amount of feedback required is small, only enough to make up for the tank circuit losses. It is analogous to the pendulum of a clock; once swinging, it needs only a small push to make up the losses due to friction. With only a slight "push" required to make up for circuit losses, the output signal applied to the grid need not be the complete sine wave. To provide this slight push a class-C amplifier is used.

Oscillator Characteristics

The oscillator is self-starting. When voltage is first applied, there is no grid bias, causing heavy plate current flow. The large pulse of current flows through the tickler coil, building a strong field about it. This induces a voltage in the tank circuit, which starts to oscillate. The procedure is called shock excitation. The signal swing at the grid circuit causes the grid to draw current on the positive alternations, building up to the required bias.

The tank circuit may be coupled to another circuit. The coupling could cause the tank circuit to become "loaded down," reducing the amplitude of the oscillations. The signal swing being reduced, the tips of the positive alternations may not drive the grid voltage positive. There is then no grid current flow. The capacitor discharges and for a short time maintains the proper bias. Soon the capacitor discharges to a point where the grid-bias voltage is greatly reduced. After a few cycles the bias will have gone sufficiently positive-going to cause the tips of the alternations to drive the grid positive, causing grid current to flow again. The voltage drop across the grid-leak resistor again develops the correct bias. At the same time the positive grid causes increased plate-current pulses to flow, maintaining the feedback. The end result is to have the oscillator again running with its original values.

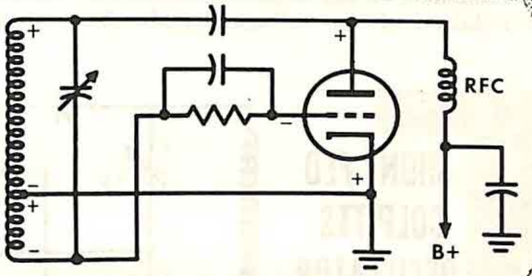
The OSCILLATOR IS SELF REGULATING

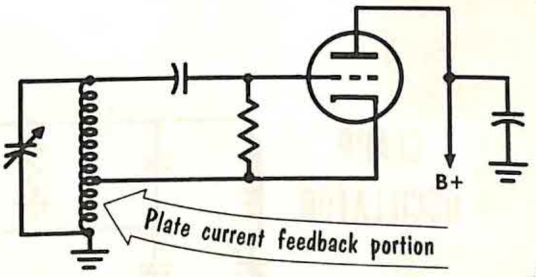


Hartley Oscillator

One of the most popular oscillators is the Hartley, named after its inventor. It uses a single tapped coil and capacitor in the tank circuit.

Taking one alternation of the circuit, the top, or plate end of the coil is positive, the bottom, or grid end is negative. The cathode is placed at the tap on the coil. To vary the feedback the tap can be moved. This controls the value of feedback signal applied between cathode and grid. With the grid signal negative with respect to the cathode, the output pulse at the plate is 180° out of phase, or positive. Coupling the output pulse to the positive end of the coil provides the proper in-phase feedback. For the following alternation the top of the tank coil is negative; the bottom positive. The grid has a positive signal with respect to the cathode. The pulse at the plate is 180° out of phase, or negative-going. This is coupled to the negative end of the coil, again giving the proper in-phase feedback.


SHUNT-FED HARTLEY OSCILLATOR

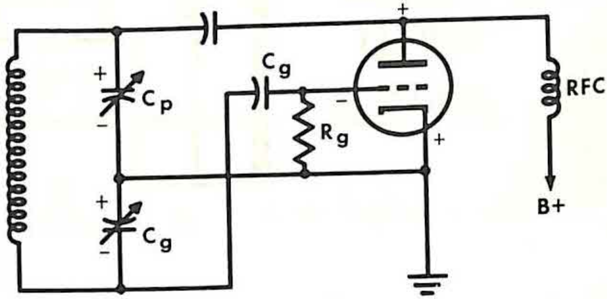

SERIES-FED HARTLEY OSCILLATOR

It is desirable to free the plate of the plate load and feedback task, using it merely as an attracting force for the electron stream. In the circuit shown, feedback is accomplished by plate current flow through that portion of the coil that is in the cathode circuit.

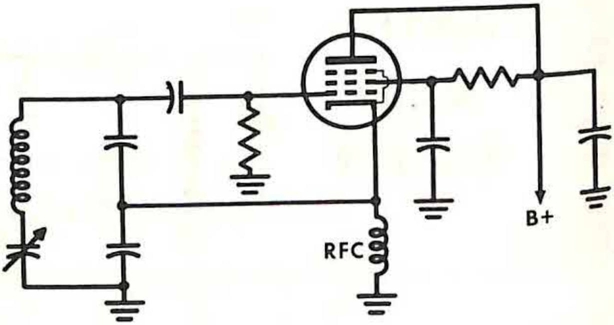
Colpitts and Clapp Oscillators

The most popular type of capacitive-coupled oscillator is the Colpitts, also named after its inventor. To prevent plate current from flowing through the tank circuit, it is shunt-fed. Its operation is similar to that of the Hartley oscillator. Instead of a tapped coil, there is the equivalent in two variable capacitors forming a voltage divider for the signal voltage. The voltage developed across the reactance of the grid circuit capacitor C_g, is applied between the grid and cathode. As shown, the grid is negative in respect to the cathode. The signal at the plate is a positive-going pulse which provides the in-phase feedback to the positive end of the coil. To vary the value of feedback the relation of the voltage division between the two capacitors must be varied. To vary the frequency of the tank circuit, both capacitors should be varied. Quite often the frequency of the tank circuit is varied by using a slug-tuned coil to change its value of inductance.

SHUNT-FED COLPITTS OSCILLATOR



CLAPP OSCILLATOR



The Clapp oscillator closely resembles the Colpitts oscillator. The major differences are the use of a pentode, with the plate bypassed, placing it at a-c ground potential. With no plate load, the plate voltage is relatively constant, where the plate voltage of a triode varies, in turn varying the transconductance of the tubes. Another difference is the use of a series-tuned resonant circuit. This allows the use of fixed values of capacitors for the voltage divider. The Clapp oscillator provides stability of a high order.

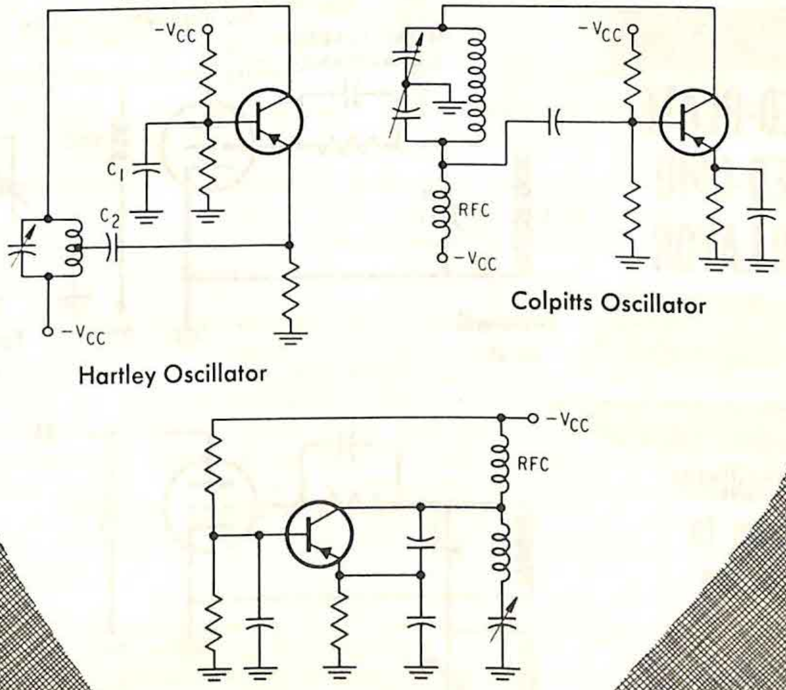
Transistor Oscillators

Transistor circuits are usually used in low-power portable transmitters for Marine, Citizens-Band, amateur, and business communications.

The circuits of the transistor versions of the Hartley, Colpitts, and Clapp oscillators illustrate that they are identical to their vacuum tube counterparts, with the transistor providing the amplified power that is fed back to sustain the tank circuit oscillations.

The Hartley oscillator using a tapped coil has the base at ground with bypass capacitor C1, and the tap on the coil coupled to the emitter through coupling capacitor C2. The coil tap is selected to match the low impedance found in a transistor circuit. In both the Colpitts and Clapp circuits an r-f choke is used as an inductive collector load to develop the feedback signal. In all three circuits shown, bias is fixed, using a voltage divider to provide the base bias. Self-oscillation starts as a result of the amplified noise being fed back and growing in amplitude until a sufficient noise signal is reached to start excitation of the tank circuit.

TYPICAL TRANSISTOR OSCILLATORS



Hartley Oscillator

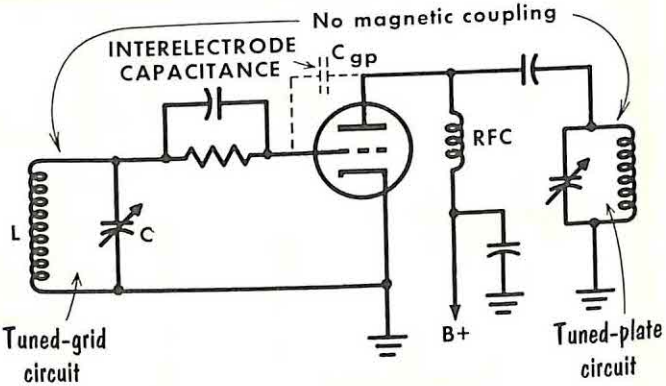
Colpitts Oscillator

Clapp Oscillator

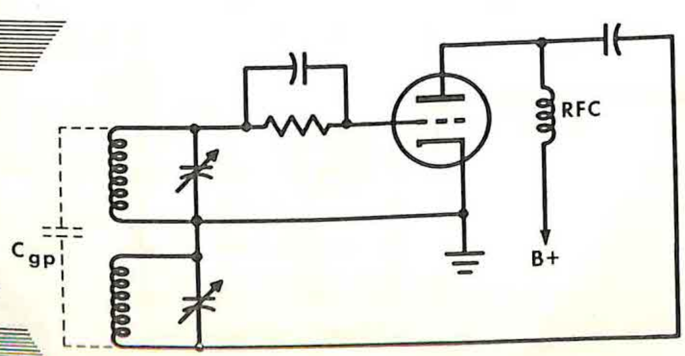
The Tuned-Plate Tuned-Grid Oscillator

The tuned-plate tuned-grid (TPTG) oscillator uses a tuned circuit in both the plate and the grid circuits; the circuits are not inductively coupled. This type of oscillator may be used over a wide range of frequencies. However, because of reduced feedback between plate and grid at low frequencies, the TPTG oscillator is not particularly satisfactory at low frequencies. The feedback necessary to maintain oscillations is coupled from the plate circuit to the grid circuit by means of the interelectrode capacitance between plate and grid. Conventional grid-leak bias is used, with the r-f signal bypassed around the power supply.

In general, the frequency of oscillation is determined by the tuned L-C circuit having the higher Q. In most cases this is the grid-tank circuit. However, the natural oscillation frequency of the grid tank is lowered by the presence of the large effective input capacitance in parallel with the tank capacitance. To compensate for this, the grid-tank circuit must be tuned to a frequency slightly higher than called for, by reducing the capacitance of C. The plate-tank circuit must be tuned below the operating frequency to obtain the proper phase relations for oscillation. When redrawn, the similarity of the TPTG to the Hartley oscillator becomes apparent.



TUNED-PLATE TUNED-GRID OSCILLATOR

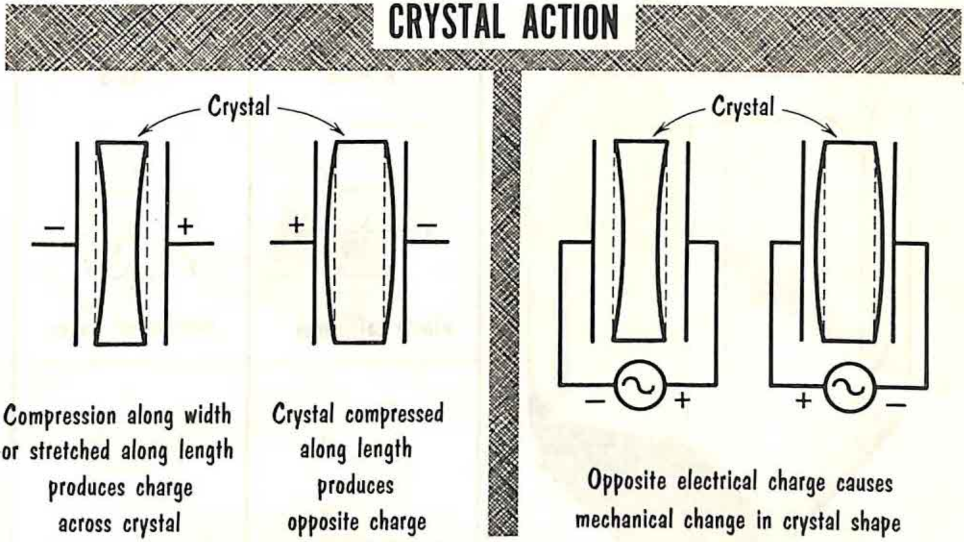


The oscillator redrawn to show the similarity to a Hartley oscillator

Action of Crystals

Types of crystals occasionally abbreviated as "xtal" exhibit the piezoelectric effect. The word piezo is a Greek word for pressure, or pressing. Piezoelectric then is "electricity from pressure." This describes the action of a quartz crystal. When squeezed, or compressed, a difference of potential is developed between its two faces. Increased pressure results in increased potential difference. Compressing a piece of quartz crystal in its width (A) causes it to develop a potential with each side having an opposite polarity. When the crystal is squeezed so that it bulges outward (B), the charge across each face reverses polarity.

CRYSTAL ACTION



Compression along width or stretched along length produces charge across crystal

Crystal compressed along length produces opposite charge

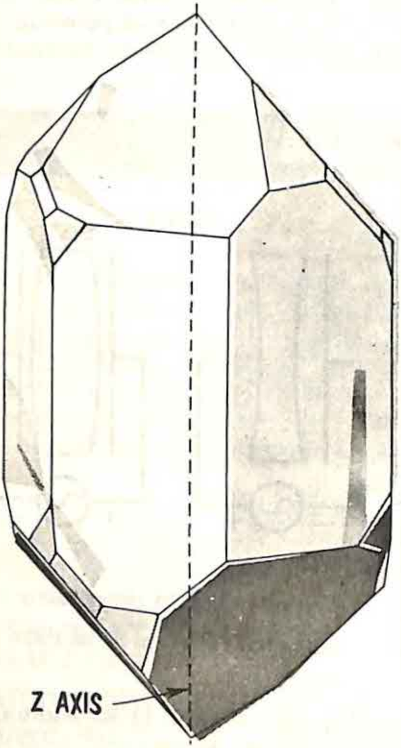
Opposite electrical charge causes mechanical change in crystal shape

In addition to generating a voltage, application of an alternating voltage to the two sides of the crystal causes it to vibrate mechanically. These vibrations become very strong when the frequency of the applied voltage is the same as the mechanical resonant frequency of the crystal (determined by its size and shape). These strong vibrations at the resonant frequency in turn generate a strong alternating voltage at the same resonant frequency. When the applied alternating voltage is sufficient to overcome the mechanical losses of the vibrating crystal, the generated alternating voltage of the crystal appears as a constant-frequency signal voltage that can be used as an L-C tank in an oscillator circuit.

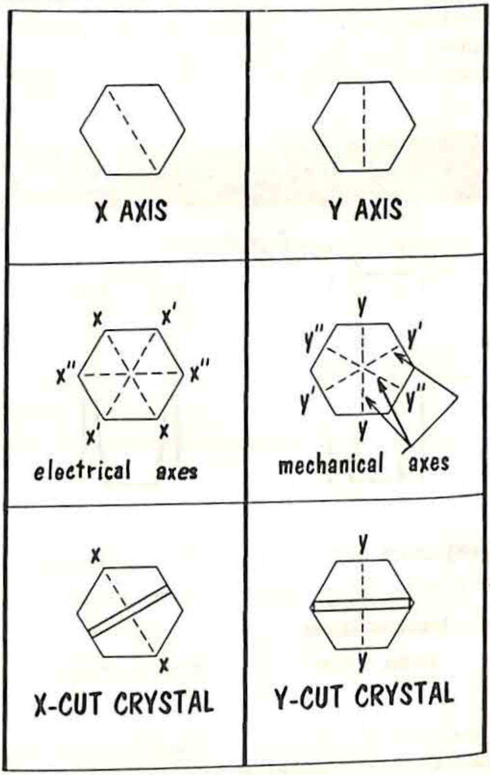
Many crystals exhibit the piezoelectric effect, but three particular types have been found to be most useful: Rochelle salt, tourmaline, and quartz. Rochelle salt is the most active crystal, generating the greatest amount of voltage for a given mechanical strain. However, quartz crystal is the most common type used for crystal oscillator circuits. It is inexpensive, rugged, stable, and can withstand reasonably high temperatures.

Crystal Cuts

HEXAGONAL CRYSTAL



QUARTZ CRYSTAL AXES AND CUTS



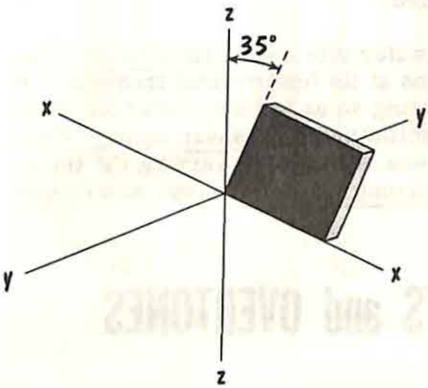
Natural crystals are found in various shapes, but those used for electronics are six-sided, or hexagonal. The crystal is divided and identified by various imaginary axes running through it. The Z axis, sometimes referred to as the optical axis, runs from end-to-end of the crystal. Strain or stress applied along the Z axis causes no piezo effect. Drawing a line from one of the six corners to an opposite corner produces an X axis. The three combinations of corners are labeled X, X', and X''. The X axes are called the electrical axes because they provide the greatest piezoelectric effect. Joining opposite faces produces Y axes.

Crystal wafers are cut from the natural crystal, called the mother stone, or crystal. The thickness of the wafer, and the method in which it is cut or oriented to the mother stone will determine its frequency and temperature characteristics. The thinner the crystal wafer, the higher the frequency at which it can vibrate. A crystal wafer cut so as to have its two flat sides, or faces, facing an X axis, is called an X-cut crystal. An X-cut crystal is sliced from the mother crystal at a Y-axis angle. A crystal wafer having its two faces perpendicular to a Y axis is called a Y-cut crystal. Y-cut crystals are sliced at an X-axis angle.

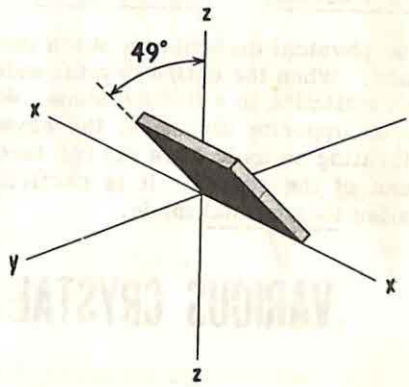
Temperature Coefficient

To obtain improved characteristics a wafer may be cut from the mother crystal on axes that are neither X, Y, or Z. The wafer may be cut to appear similar to a Y-cut crystal, but actually be tilted about the X axis at a 35° clockwise angle. This changes the notation of the crystal to an AT-cut. When the wafer is similar to a Y-cut crystal but is rotated to a 49° counterclockwise angle, it is called a BT-cut.

A vital characteristic of a wafer crystal is its temperature coefficient. This refers to the change in frequency that occurs when the temperature surrounding the crystal changes. An increase in temperature causes the crystal to expand, changing its resonant frequency (the crystal "drifts").



AT-CUT CRYSTAL



BT-CUT CRYSTAL

The variations in frequency are expressed in p/m (parts per million), sometimes written as ppm, or hertz per megahertz, for an increase in temperature of 1°C. The combined notation reads p/m°C. The change in frequency, or drift, may be upward to a higher frequency for a positive or plus coefficient, or it may be downward to a lower frequency for a negative or minus coefficient. A crystal wafer having no frequency drift with changes in temperature is rated as having a zero temperature coefficient.

Some crystals have poor temperature coefficients. An example might be a rating for a crystal of -20 hertz per megahertz per degree centigrade, abbreviated -20p/m°C. This indicates that the crystal will provide an output resonant frequency 20 hertz per megahertz lower per MHz for each °C increase in temperature. The exact value of drift varies with the type of cut and the thickness of the crystal. The AT-cut, and BT-cut wafer crystals have better temperature coefficients than the X-cut, and Y-cut crystals. An AT-cut crystal may have a rating of 0 p/m°C at 45°C. This means that keeping the temperature of the crystal close to 45°C will keep the output frequency constant. When operated at 85°C the same crystal may drift as high as ±20p/m°C.

Accn- 16740

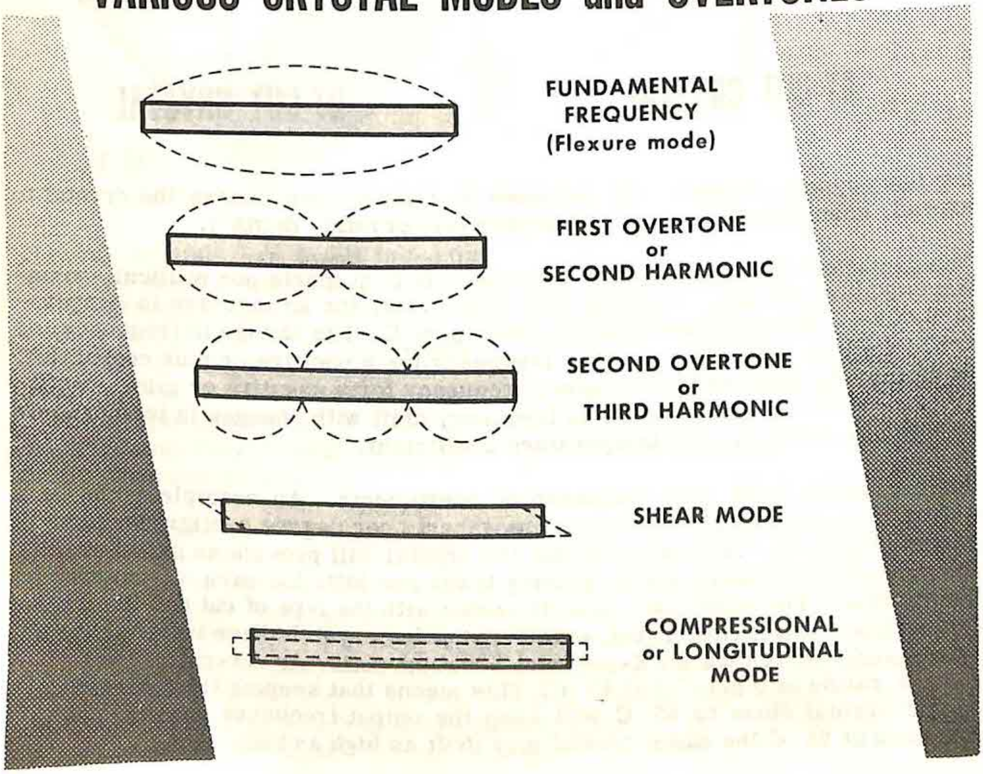
Oscillator Harmonics

When the crystal wafer has applied to it an a-c signal of the same frequency to which the crystal is mechanically resonant, the crystal develops strong vibrations. If not controlled, the vibrations may become excessive and fracture the crystal. When the entire crystal vibrates, the frequency at which it vibrates is called the fundamental frequency.

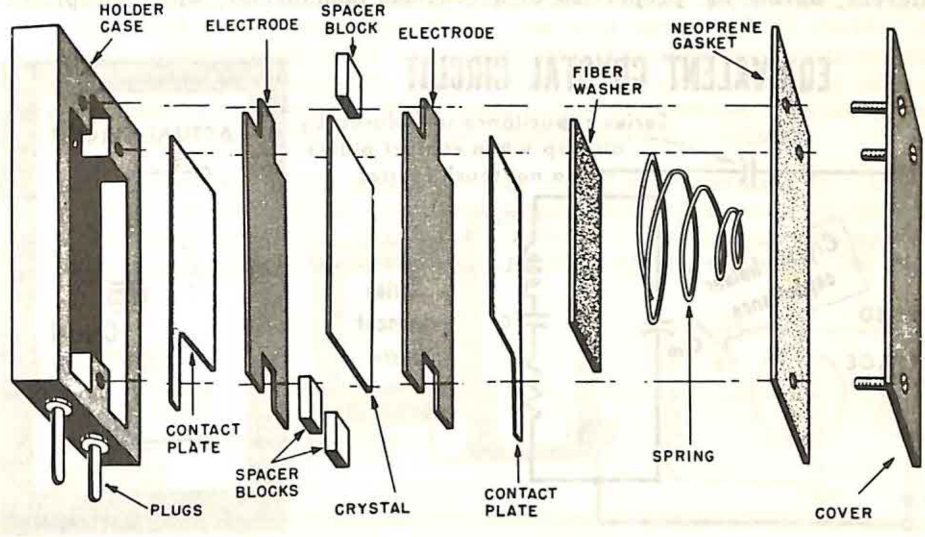
The same size crystal may vibrate in two motions, or wavelengths of the fundamental. This provides a frequency that is two times the original fundamental frequency, called the first overtone, or the second harmonic. When the same crystal vibrates in three wavelengths of the fundamentals, the second overtone, or third harmonic, is generated.

The physical direction in which the crystal wafer vibrates, called mode, may vary. When the entire crystal wafer vibrates at its fundamental frequency it is oscillating in a flexure mode. When vibrating so as to have each face move in an opposite direction, the crystal is oscillating in a shear mode. When vibrating so as to have the two faces compress and expand, varying the thickness of the crystal, it is oscillating in a compressional mode, sometimes called longitudinal mode.

VARIOUS CRYSTAL MODES and OVERTONES


FUNDAMENTAL FREQUENCY (Flexure mode)
FIRST OVERTONE or SECOND HARMONIC
SECOND OVERTONE or THIRD HARMONIC
SHEAR MODE
COMPRESSIONAL or LONGITUDINAL MODE

Crystal Holders



CONSTRUCTION of "PRESSURE SANDWICH" TYPE MOUNT

The crystal wafer is carefully ground to exact thickness for resonance at the desired frequency. The crystal must be kept perfectly clean and placed in a special crystal holder. A basic holder consists of two metal electrodes to make contact with the faces of the crystal, with an air gap to minimize damping of the vibrations. The clamp holder is identical to the basic type, except that the crystal is firmly clamped between the two electrodes. The symbol for a crystal holder closely represents its physical construction.

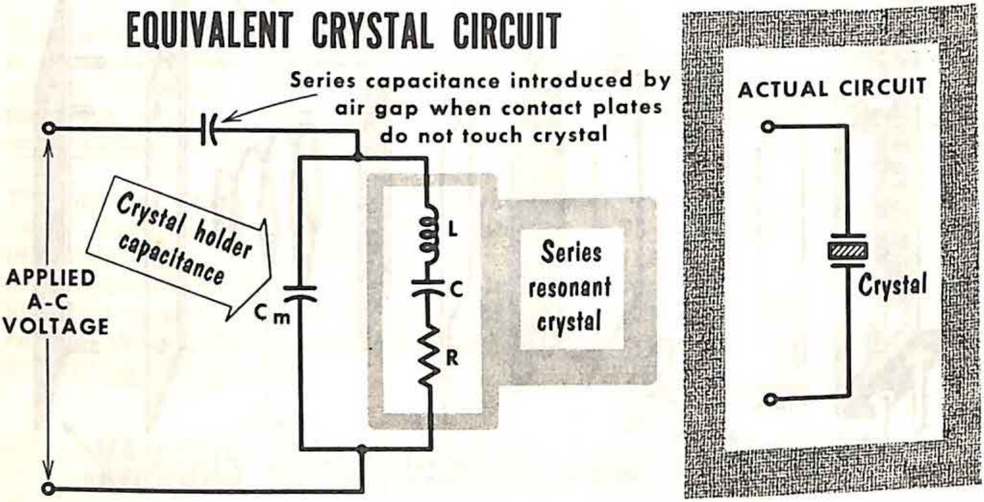
The physical construction of the crystal holder varies widely, some taking the shape of a "pressure sandwich" in which the crystal is clamped in a spring-mounted sandwich and then placed in a holder of the type shown. Other holders may clamp the crystal between tuned lengths of wire, or clamp the crystal at its edges.

The holder may take other forms such as that shown enclosed in a vacuum, which mounts in a standard octal socket. Other holders use various sockets depending upon their pin dimensions; most crystal holders will fit in standard tube sockets.

A special crystal oven can be used to maintain the crystal at a near-constant temperature to prevent oscillator drift. The crystal oven is designed to keep the temperature of the crystal at a constant higher value than the surrounding or ambient temperatures. This prevents ambient temperature changes from affecting the oven-controlled crystal. Operating the crystal at a higher temperature is of little consequence; more important is that the oven temperature be held constant.

Crystal Characteristics

The crystal wafer, in its crystal holder, represents a circuit component. When shown as a symbol in a schematic diagram it appears merely as a slab of crystal between two electrodes. As a circuit component it appears vastly different, having the properties of a resonant tank circuit, with appropriate values of L, C, and R. The capacitance of the electrodes, or crystal mounting device is C_m. The series resonant action of the crystal is represented by L, C, and R. R represents the electrical equivalent of the mechanical friction present when the crystal is vibrating; C represents the electrical equivalent of the mechanical compliance (stiffness) of the crystal; L represents the electrical equivalent of the vibrating mass of the crystal. L and C of the crystal determine its series-resonant value.


EQUIVALENT CRYSTAL CIRCUIT
Series capacitance introduced by air gap when contact plates do not touch crystal
Crystal holder capacitance
APPLIED A-C VOLTAGE
C_m
L
C
R
Series resonant crystal
ACTUAL CIRCUIT
Crystal

The capacitance of C_m is high, and in parallel with the series-resonant circuit of the crystal, forming a parallel-resonant circuit. The series-resonant circuit of the crystal is lower in frequency than the parallel-resonant circuit. When a series-resonant circuit is above resonance, the increased reactance of L, and decreased reactance of C, causes it to appear as an inductive circuit. The parallel-resonant circuit of the combined crystal holder capacitance, and the crystal, is slightly higher in frequency than that of the series-resonant crystal itself. At the higher resonant frequency of the parallel-resonant circuit, the crystal appears as an inductive circuit.

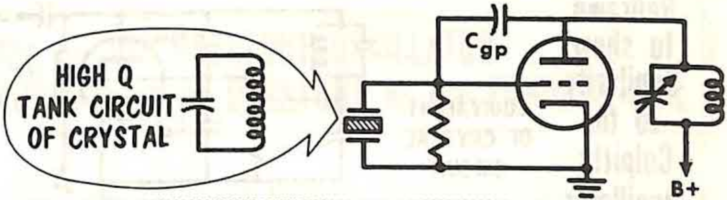
Parallel resonance occurs when the X_C of C_m is equal to the X_L of the series-resonant circuit of the crystal. The actual values of resonant frequencies of both the series-resonant circuit of the crystal and the parallel-resonant circuit of the crystal and holder, is fairly close. This results in a parallel-resonant circuit of extraordinarily high Q. A normal high-Q L-C tank circuit might have a Q of 100; the Q of a crystal-tank circuit could well be 30,000.

Basic Crystal Oscillator

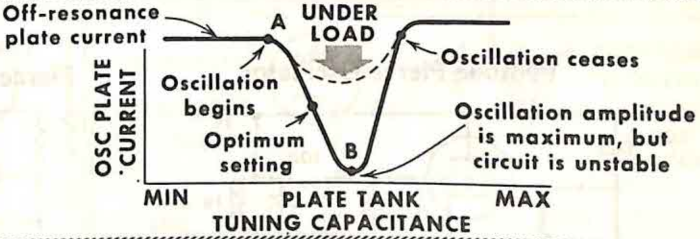
Note the resemblance of the crystal oscillator to the TPTG type. The crystal replaces the grid tank, and feedback is through grid-plate capacitance. The high-Q grid circuit requires critical plate-tank circuit adjustment for correct oscillator operation. As the tuning capacitance in the plate circuit varies from minimum to maximum capacitance, the first signal of plate current reduction, A, indicates the start of oscillations. As capacitance is increased, the oscillations grow stronger, indicated by a continuous decrease of plate current, until B is reached. When capacitance is increased beyond B, oscillation ceases, and plate current immediately rises to maximum.

Optimum operation occurs between points A and B. Operating too close to these points causes critical conditions where small changes in circuit constants may stop oscillation. When the circuit is loaded (energy is coupled to another circuit), the plate-current dip is not as great. However, the dip is still there, and careful tuning is required to place the plate current value between A and B. In addition to monitoring plate current, the grid current or bias voltage developed across the grid resistor may also be monitored. Grid current values are the opposite of plate current values – as the plate current dips, the grid current rises. Use of a beam-power pentode increases output, but the crystal receives less feedback due to the reduced plate-to-grid interelectrode capacitance of a pentode. However, a small-value external capacitor may be placed from plate to grid for sufficient feedback.

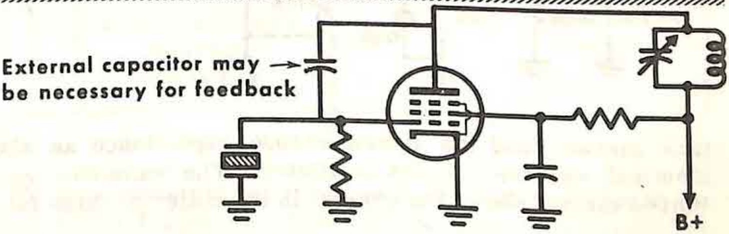
CRYSTAL OSCILLATOR BASIC CIRCUIT



RESONANCE CURVE

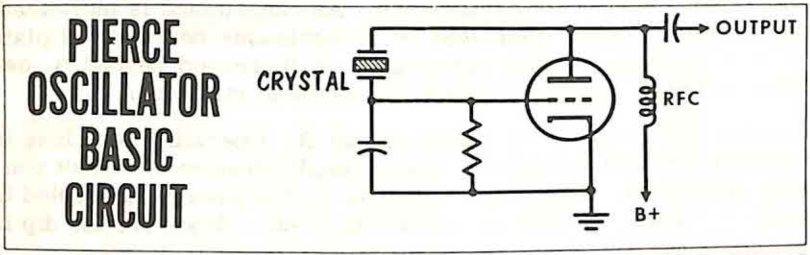


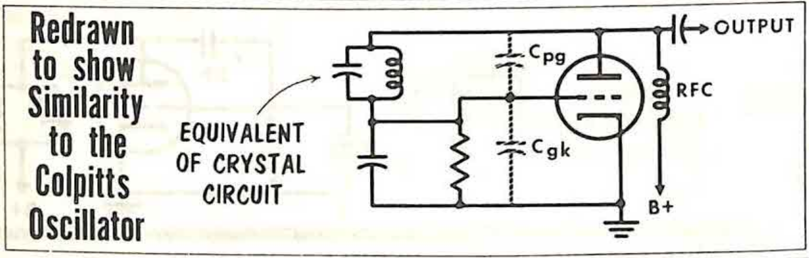
PENTODE CRYSTAL OSCILLATOR

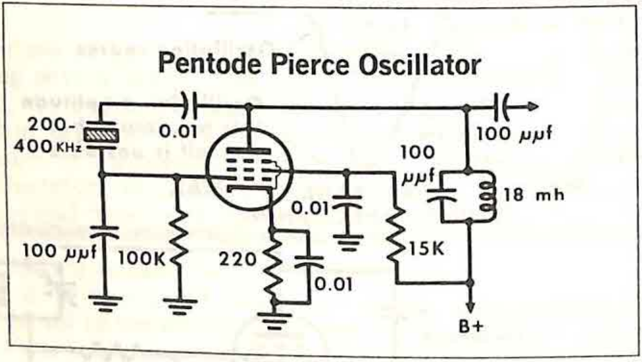


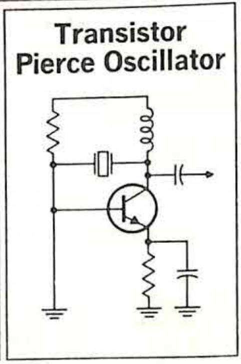
Pierce Oscillator

The Pierce-oscillator circuit provides high stability with a simple circuit that requires no L-C tank circuit. The lack of a tank circuit makes the oscillator convenient for use with numerous crystals that may be switched into position as desired. With the circuit redrawn, the crystal represented as a tank circuit, and the interelectrode capacitance as shown, the circuit is identical with the Colpitts oscillator. The transistor operated version of the Pierce circuit shows the crystal in the collector-base feedback path.


PIERCE OSCILLATOR BASIC CIRCUIT


Redrawn to show Similarity to the Colpitts Oscillator


Pentode Pierce Oscillator


Transistor Pierce Oscillator

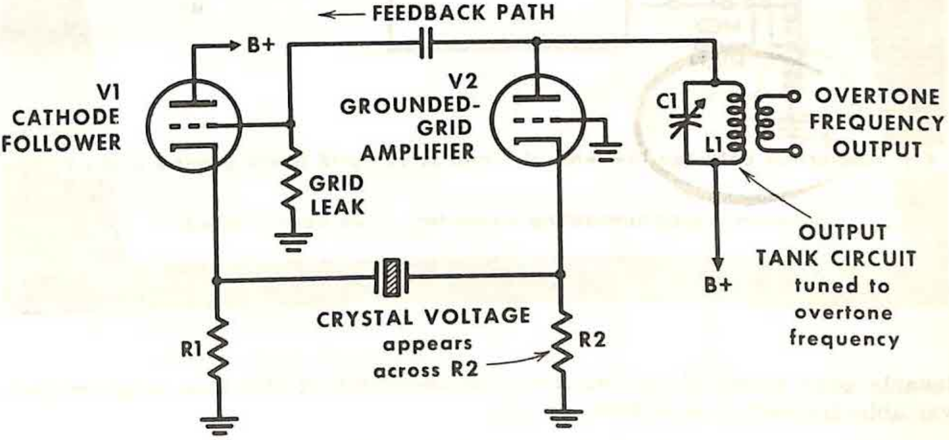
The use of a pentode for a Pierce oscillator is quite common. The circuit is identical with regard to placement of the crystal. The additional components (aside from the screen-bypass capacitor and voltage-dropping resistor) are the cathode-bias resistor, cathode-bypass capacitor, and the coupling capacitor between the plate and crystal holder. The small bias developed in the cathode circuit is merely a safeguard. With the crystal removed the tube will have a small amount of bias to keep the plate current from reaching an excessive value. The capacitor between the plate and crystal holder removes B plus from the crystal holder and crystal.

The Crystal-Overtone Oscillator

Sometimes the desired frequency of operation is so high that a crystal ground, so that its fundamental frequency is the desired frequency, would be so thin as to be easily fractured. An alternative method of achieving crystal control of the high frequency is to use an overtone crystal. An overtone crystal is a special cut that affords more than the normal output at a particular overtone or harmonic frequency. It may be labeled 33.3 MHz and be used to generate this frequency although its mechanical resonant or fundamental frequency is 11.1 MHz. Thus the crystal is operating at its third harmonic.

The Butler overtone oscillator is a popular circuit for an overtone oscillator. It is simple and has high frequency stability. Tube V1 is a cathode follower, while tube V2 is a grounded-grid amplifier. The cathodes of the two tubes are coupled to each other via the crystal, which, at its overtone frequency, is series resonant and therefore presents very low impedance (resistance). The plate tank L1-C1 in the grounded-grid amplifier plate circuit is tuned to the overtone or oscillator output frequency. Note that the plate of the amplifier stage (V2) is coupled to the control grid of the cathode follower (V1). A pulse appearing in V2 when the operating voltage is first applied, develops an output voltage that is fed back to V1, there to cause a voltage to appear across the cathode resistor R1. This voltage starts the crystal vibrating. The resultant voltage developed by the crystal appears across R2. With the control grid of V2 connected to ground, the crystal voltage applied across R2 appears between the cathode and control grid of V2. An amplified version appears in the plate circuit of V2 and is fed back to V1. The action is repeated until sustained oscillations are generated.

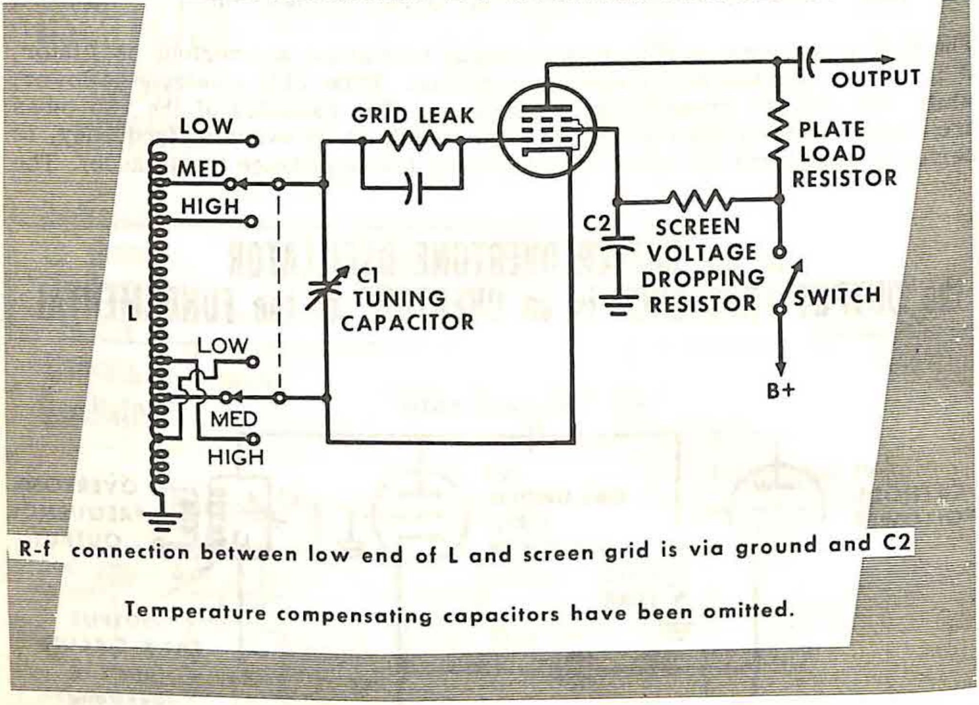
In the BUTLER OVERTONE OSCILLATOR the OUTPUT FREQUENCY is an OVERTONE of the FUNDAMENTAL



The Variable-Frequency Oscillator (VFO)

Many transmitters are designed to function anywhere within one or more bands of frequencies. Amateur radio stations, also known as "ham" stations use such transmitters, as do some other services. To permit such operation the oscillator portion, as well as other parts, of the transmitter are made tunable over bands of frequencies. An oscillator of this kind is known as a variable-frequency oscillator, or vfo.

A BASIC VARIABLE-FREQUENCY L-C ELECTRON-COUPLED OSCILLATOR



R-f connection between low end of L and screen grid is via ground and C2

Temperature compensating capacitors have been omitted.

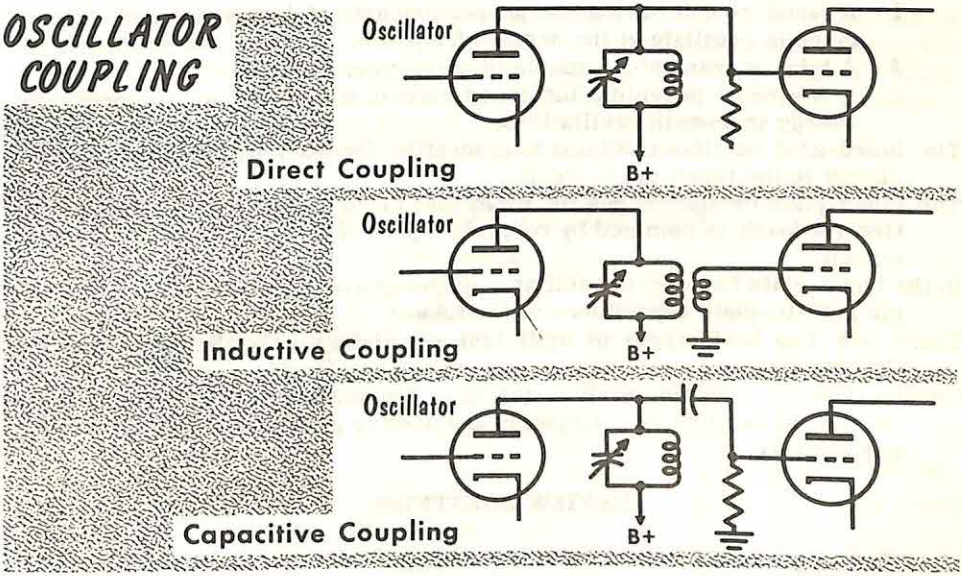
Variable-frequency oscillators are L-C oscillators. Most often they switch in different values or taps on a coil to select the desired band of frequencies. The variable C affords the choice of the exact desired frequency. When used in transmitters, variable-frequency oscillators are similar to the variable frequency heterodyning (local) oscillators used in superheterodyne receivers.

The number of frequency bands covered by a variable-frequency oscillator may be from one to as many as allowed for in the design. Usually the vfo is an integral part of the transmitter. Sometimes it is a separate device connected to the remainder of the transmitter. We show one type of circuit used for generating oscillations, but the variable-frequency oscillator may use any one of a number of other circuit configurations.

Oscillator Coupling and Loading

To use the oscillator circuits previously discussed the signal must be coupled to additional circuits. Although the output of an oscillator circuit could be coupled to an antenna, it most often is coupled to additional circuits. Shown here is direct coupling of the output tank circuit to the grid of the following stage. Direct coupling is rarely used; it provides no isolation between stages, and requires careful application of voltages. Inductive coupling has the output coupled to a secondary winding of a transformer. Quite often the secondary is also a tuned circuit for maximum signal coupling. Capacitive coupling will couple the full output signal to the succeeding stage.

The stage following derives its energy from the oscillator circuit. The removal of energy from the oscillator is termed loading. Oscillator circuits are to a degree self-regulating, and normally make up for circuit loading. Despite this, loading of the oscillator circuit can make itself felt in other directions. Coupling to the output circuit is paralleling the output circuit; this changes the values of the output-tank circuit causing it to be mistuned, requiring realignment. Loading the oscillator output-tank circuit also reduces the Q of the circuit, reducing the feedback and efficiency of the oscillator. A low-Q tank circuit can readily have its output frequency shifted, since the tank circuit will easily resonate over a wide band of frequencies.



To keep adverse effects to a minimum it is best to load the oscillator output as little as possible. Minimum loading is often accomplished by the use of electron coupling. The electron-coupled oscillator separates the frequency-determining portion of the oscillator from the output-tank circuit, providing a minimum of loading.

Basically, the radio transmitter is a device that generates an electrical signal that can be fed to the antenna, and from there radiated into space.

Large transmitter tubes produce large amounts of heat which must be removed to prevent damage to the tubes and associated circuits. This heat is produced mainly at the plate, but also at any grid drawing current.

Heat removal can be accomplished by natural air currents, forced-air cooling, or water cooling. Blackening the plate also assists in heat removal. Grids drawing large currents are constructed with internal tubing through which water is circulated.

Materials with a high melting point, such as molybdenum, tantalum, and tungsten, are used in the construction of grids.

Typical plate materials are graphite, copper, molybdenum, nickel, tantalum, and tungsten. Nickel is used for low-power transmitter-tube plates, graphite and molybdenum for medium-power, tantalum for high-power, and tungsten for extremely high-power.

To produce oscillations, the oscillator circuit must have the following characteristics.

1. A tuned circuit having the proper amounts of inductance and capacitance to oscillate at the desired frequency.
2. A tube or transistor capable of amplifying a signal.
3. A means of providing the tuned circuit with sufficient regenerative energy to sustain oscillations.

The tuned-grid oscillator obtains regenerative feedback by coupling the plate circuit to the tuned-grid circuit.

The tuned-plate oscillator has its tuned circuit on the plate side. Regenerative feedback is obtained by coupling a part of the oscillation to the plate circuit.

In the tuned-plate tuned-grid oscillator, regenerative feedback occurs through the grid-to-plate capacitance of the tube.

There are two basic types of split-tank oscillators – the Hartley, and the Colpitts.

Certain types of crystals, such as quartz or tourmaline, can be used as tuned circuits in oscillators. Crystals are used to give frequency, precision, and stability.

REVIEW QUESTIONS

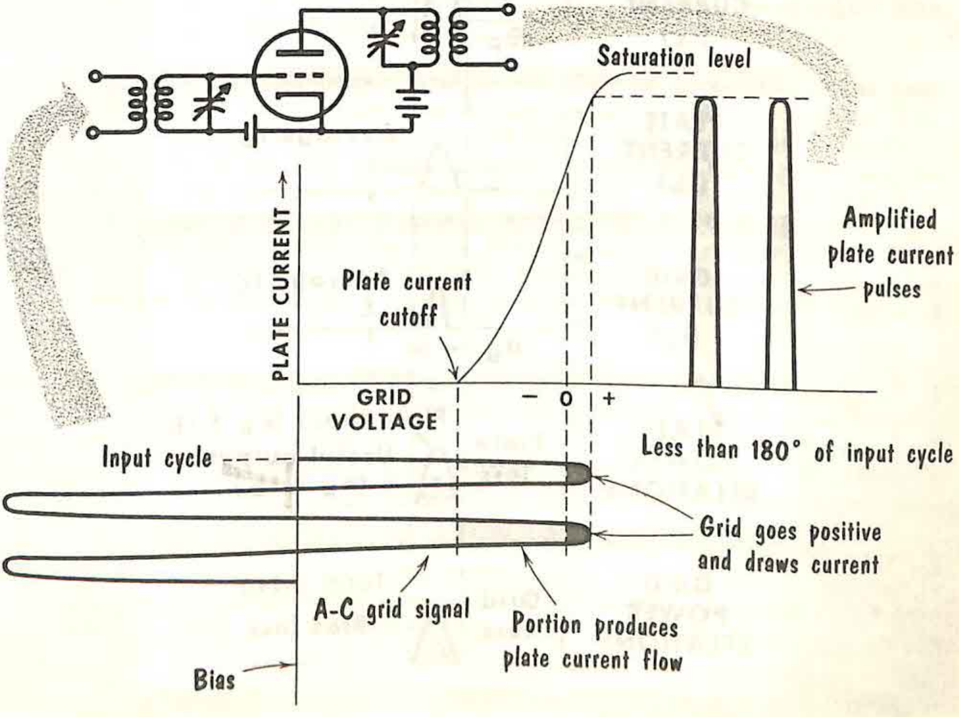
1. What is the basic function of a transmitter?
2. Basically, how do transmitting tubes differ from receiving tubes?
3. State two methods of removing heat from a transmitting tube.
4. What type of filament material is used in high-power transmitters?
5. How is energy coupled from the plate circuit to the grid circuit in the TPTG oscillator?
6. What are the proper conditions for producing regenerative feedback in the TPTG oscillator?
7. What is the function of a crystal as used in an oscillator?
8. What are the characteristics of an X-cut crystal?
9. What is meant by the "piezoelectric" effect?
10. What is meant by the temperature coefficient of a crystal?
11. What effect does the crystal mounting have on the equivalent circuit of the crystal?
12. How does the Hartley oscillator differ from the Colpitts oscillator?

The Class-C Amplifier

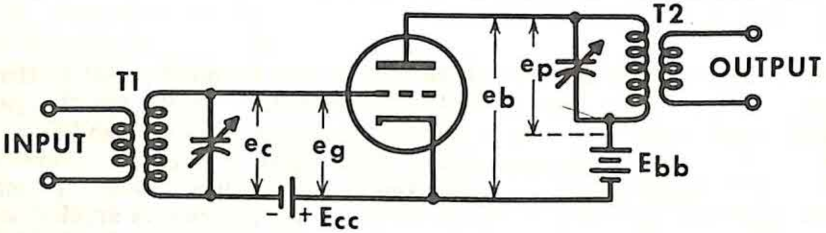
A class-C amplifier is biased well beyond (1.5 to 4 times) cutoff so that plate current flows for less than 180° of the input cycle. On the positive peaks of the grid-input signal the grid is generally driven positive, and as a result, draws current. In the absence of any input-signal voltage, the plate current is zero, and remains zero until the signal voltage has a positive amplitude greater than the applied grid bias. When the input signal is applied and grid current flows, the rise in plate current takes place along the linear portion of the characteristic curve – ideally up to, but not exceeding, the saturation level.

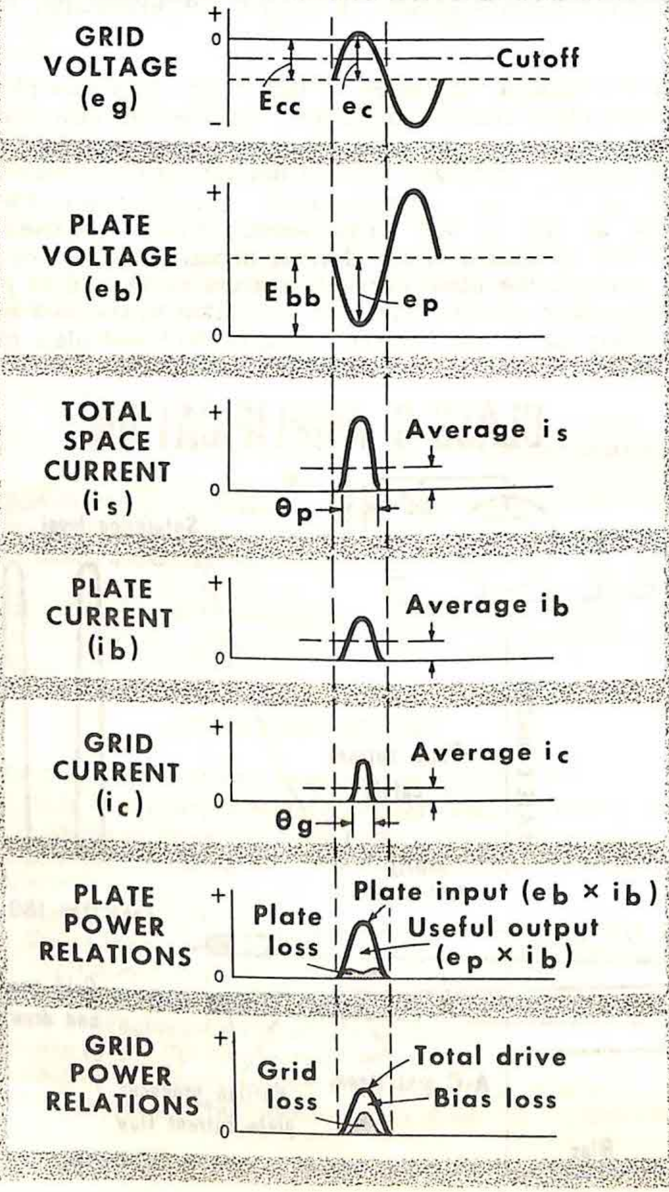
A feature of the class-C amplifier is that it affords higher plate circuit efficiency than any other class of amplifier. This is the efficiency with which the d-c power supplied to the plate circuit is converted into amplified a-c energy. The class-C amplifier (biased beyond cutoff) consumes power only during a portion of the input-signal period. The efficiency of a class-C amplifier may be as high as 80%. This amplifier cannot be used to reproduce variations in the waveform of the driving signal because, regardless of the input-signal voltage, the plate current appears as individual pulses. When amplifying sine-wave signals, the high distortion introduced by the class-C amplifier is overcome by the flywheel effect of the tuned-plate circuit.

CLASS-C AMPLIFICATION


Saturation level
PLATE CURRENT →
Amplified plate current pulses
Plate current cutoff
GRID VOLTAGE
− 0 +
Input cycle
Less than 180° of input cycle
Grid goes positive and draws current
A-C grid signal
Portion produces plate current flow
Bias

CURRENT and VOLTAGE in CLASS-C AMPLIFIERS





Class-C Amplifiers (Cont'd)

A typical Class-C amplifier is shown, with the input signal supplied through tuned transformer T1. The output is developed by the r-f signal appearing across the parallel resonant circuit T2. The various voltage and current relationships in the circuit are shown beneath the circuit. The signal voltage e_c is developed across the tuned circuit T1.

The Class-C amplifier operates with grid bias much greater than cutoff. Therefore, the grid excitation voltage causes plate current to flow during only part of the cycle. During the remainder of the cycle the voltage on the grid is below the cutoff value, the plate current i_b is zero, and the corresponding plate voltage e_b rises to its highest value, or E_{bb}. Since no plate current flows, the voltage drop across the plate-load impedance must be zero. The voltage drop across the load, therefore, is 180° out of phase with the grid voltage. The a-c components of the plate and grid voltages are sinusoidal because of the sharply-tuned resonant circuits.

Plate current flows when the grid voltage e_g rises above cutoff. The angle of flow of plate current is θ_p and is always less than half a cycle. Grid current flows during the angle θ_g when the grid voltage e_g becomes positive. The sum of these two currents, $i_b + i_c$, is the space current, i_s, and represents the total current leaving the cathode. The angle of grid current flow depends on the ratio of the grid bias to the peak signal amplitude. This is equivalent to saying that, in a particular amplifier, the value of the grid bias chosen determines the angle of plate current flow for a given input signal. Short angles of flow give high efficiency and low power output, whereas large angles give low efficiency and higher power output.

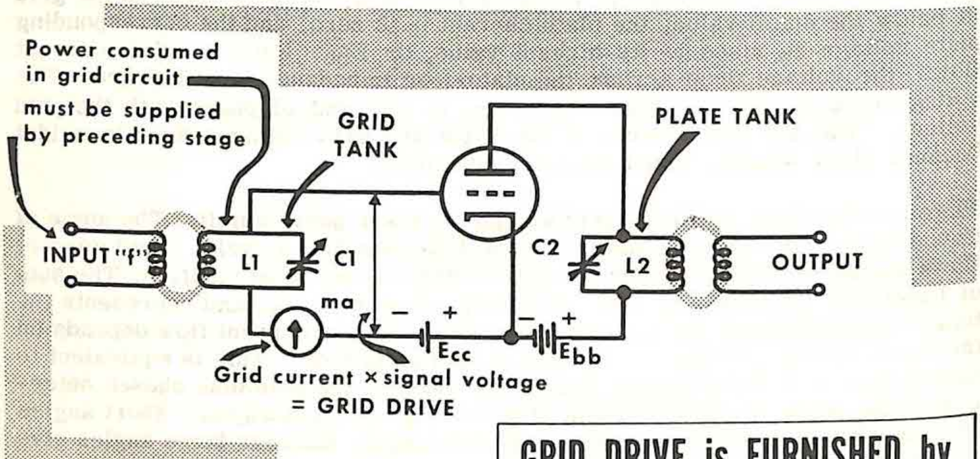
At any moment the total power input to the plate is the product of the total voltage e_b supplied to the plate, and the instantaneous plate current i_b. The power output is equal to the product of the load voltage and the plate current. The power loss at the plate is the difference between the input power and the output power. The efficiency of a Class-C amplifier is the ratio in percent of the output to input power, and is usually between 60% and 80%. This high efficiency is possible because the plate current flows only when most of the voltage drop is across the output circuit. Therefore, only a small part of the supply voltage is wasted as a voltage drop between the plate and cathode of the tube.

Since the grid of the tube swings positive and draws current during part of the cycle, power is absorbed from the excitation circuit, which is the product of the exciting voltage e_c and the grid current i_c. Some of this power is lost at the grid, and the remainder is dissipated in the bias battery. If grid-leak bias is used, the remainder is dissipated as heat in the grid-leak resistor.

Special emphasis was placed on the action of the Class-C amplifier because it represents an extremely important transmitting circuit. We will discuss it further in its numerous applications of voltage amplification and power amplification, together with methods of tuning and circuit variations.

The Class-C Tuned R-F Amplifier (The Grid Tank and Grid Drive)

The class-C amplifier as used in transmitters is a tuned r-f amplifier. A distinguishing feature is the variable-tuned parallel-resonant L-C circuit in the plate circuit. This tuned circuit is generally referred to as the plate tank. The control-grid circuit of the same amplifier stage may or may not contain a similar variable-tuned L-C circuit. When it is present it is called the grid tank. For purposes of explanation let us consider a class-C triode tuned r-f amplifier with grid and plate tanks – L1-C1 in the grid circuit, and L2-C2 in the plate circuit. The different methods of procuring the negative bias are discussed later.


Power consumed in grid circuit must be supplied by preceding stage
GRID TANK
PLATE TANK
INPUT "f"
L1
C1
C2
L2
OUTPUT
ma
Ecc
Ebb
Grid current × signal voltage = GRID DRIVE

GRID DRIVE is FURNISHED by PRECEDING STAGE

Assume a signal voltage of a single frequency "f" coupled to the grid tank. The magnitude of the signal voltage delivered to the control grid will depend on the tuning of L1-C1. When the grid tank is tuned to frequency "f", maximum signal voltage is delivered to the input circuit of the tube. If the level of the signal derived from L1-C1 is sufficient to override the applied negative grid bias, the positive peaks of the signal will drive the control grid positive and cause grid current to flow. The current will be maximum when the grid tank is tuned to resonance with the incoming signal, and will drop off rapidly each side of resonance. If we measured the signal voltage delivered to the control grid, and multiplied this voltage by the grid current, the product would be a certain amount of electrical power which is consumed in the grid circuit. This power is known as the grid drive, and is expressed in watts.

Tetrode- and pentode-type amplifiers require less grid drive than triode-type amplifiers. In all cases, however, class-C amplifiers bear a rating that states the amount of signal power (grid drive) that must be delivered to the control grid to derive maximum power from the tube. In the absence of adequate grid drive to override the applied bias, the tube will be inoperative.

Class-C Amplifiers – The Plate Circuit

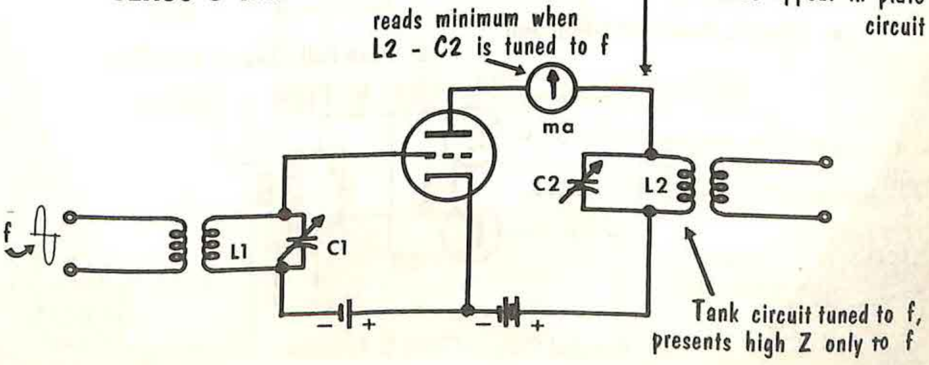
When the voltage between control grid and cathode is below cutoff, plate current flows. For any given value of applied plate voltage, the plate current is determined by the fixed grid bias, the amount of grid drive, and the state of resonance of the plate tank L2-C2. The plate tank is a parallel-resonant circuit which serves as the load for the plate circuit of the tube. As such, it presents maximum impedance at resonance.

Let us view the plate-cathode circuit inside the tube as a source of pulses of plate current, each of which consists of a number of frequencies. One of these is the fundamental frequency "f," corresponding to the frequency of the signal fed to the control grid of the tube. The others are even and odd harmonics of f, or 2f, 3f, etc. If we now visualize the plate tank tuned to the fundamental frequency of the plate current pulses, i.e., to f, then L2-C2 will present maximum impedance to the flow of this frequency component of the plate current, and theoretically zero impedance to the flow of the other frequency components of the plate current. The overall result is minimum plate current. A d-c milliammeter connected in series with the plate circuit would show minimum plate current. If the plate tank is detuned from this frequency, the impedance it presents to the flow of plate current is greatly reduced, and the plate current rises very sharply. In fact, in high-power amplifiers it can become so high as to damage the tube.

A reduction in plate current would occur if the plate tank were tuned to the second harmonic, rather than to the fundamental, except that now the decrease would not be as great as when L2-C2 was tuned to the fundamental. The reason is that the amplitude of the 2f component of the plate current is much less than the f component. Limiting the 2f component has a lesser effect on the total current than limiting the f component. The resonant plate tank would present maximum impedance to the flow of the 2f component, and theoretically zero impedance to the f component, and to frequency components higher than 2f. A corresponding action develops when the plate tank is tuned to 3f or to higher harmonics.

FUNDAMENTAL and HARMONICS in CLASS-C AMPLIFIER

f - 2f - 3f - 4f ... fundamental and harmonics appear in plate circuit


reads minimum when L2 - C2 is tuned to f

Tank circuit tuned to f, presents high Z only to f

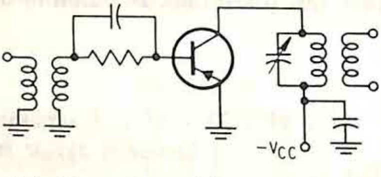
Transistor Class-C Amplifiers

The Class-C transistor amplifier shown in (A) uses the equivalent of tube grid-leak bias in the base circuit, a form of r-c self-bias that can be called "base-leak" bias. In a tube-operated power amplifier using grid-leak bias, loss of drive to the grid of the tube will result in loss of grid bias, causing excessive plate current to flow and possibly ruin the tube. In transistors, with no forward bias there is no collector current; thus the transistor protects itself when loss of drive results in loss of forward bias.

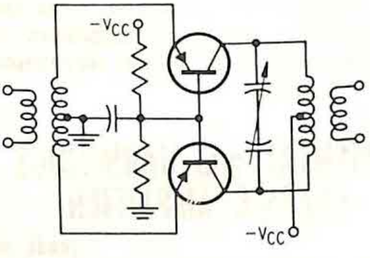
Self-bias operates as follows: On the half-cycle that causes forward conduction, the resulting base current flow will develop a voltage drop across the base resistor. During the half cycle in which base current does not flow, the discharge from the base capacitor will maintain the bias. As previously noted for grid-leak bias, the base bias voltage will average out to maintain the required level of bias voltage.

A push-pull Class-C amplifier using fixed bias is shown in (B). Note the common-base configuration, the circuit being designed for operation at high frequencies. Normally this type of circuit would require neutralization. However, the use of transistors designed for r-f has alleviated the junction self-feedback problem and neutralization is not required. A parallel output self-biased Class-C amplifier using a common emitter configuration is illustrated in (C).

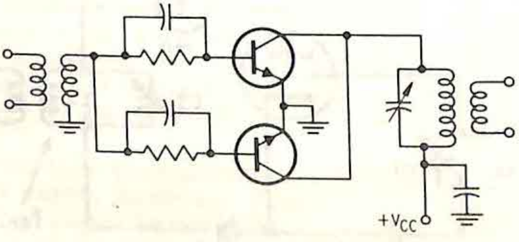
TYPICAL TRANSISTOR CLASS-C AMPLIFIERS



(A) Class-C Amplifier Using Self



(B) Push-Pull Class-C Amplifier



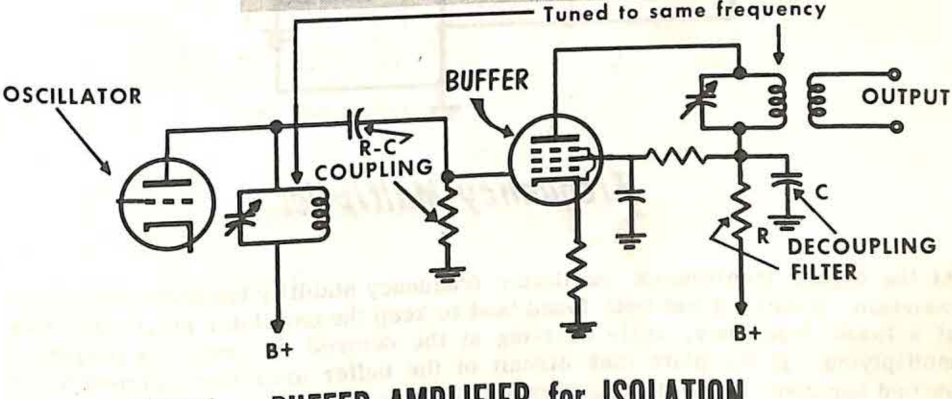
(C) Parallel Output Class-C Amplifier

Buffer Amplifiers

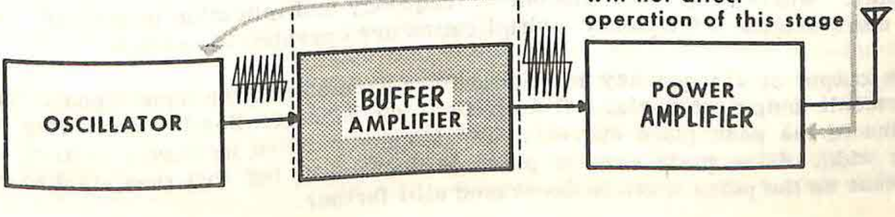
For increased power and isolation of the oscillator, a stage of amplification is placed between the oscillator and the antenna or following stages. This stage is called a buffer amplifier. Its basic function is to simply amplify, making no frequency changes. Isolating, and reducing the loading of the oscillator, improves its frequency stability. Any changes in the buffer output caused by loading from the succeeding stage is not reflected back to the oscillator; hence, buffering action.

The buffer amplifier is generally biased to operate class-A. It is designed so that the grid will not go positive and draw grid current. By doing this, the grid circuit of the buffer stage always presents a high-impedance load to the oscillator feeding it. This minimum loading produces high oscillator stability. Coupling from the oscillator to the buffer amplifier is usually of the R-C type. The output-plate circuit of the buffer has a tank circuit tuned to the oscillator frequency. The grid circuit does not use a tuned circuit, since it would then resemble a TPTG oscillator and may start oscillating. In the typical buffer circuit shown, the cathode-bias resistor is not bypassed thus providing degeneration. This acts both to keep the signal undistorted and to prevent any possible regeneration from the plate to grid circuit. In some low-power transmitters frequency multiplying is sometimes done in the buffer stage, and it may be operated class-C.

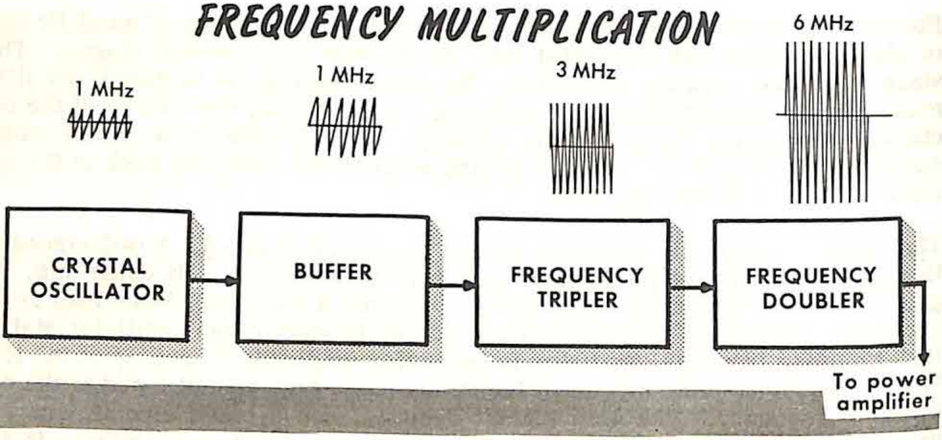
BUFFER AMPLIFIER

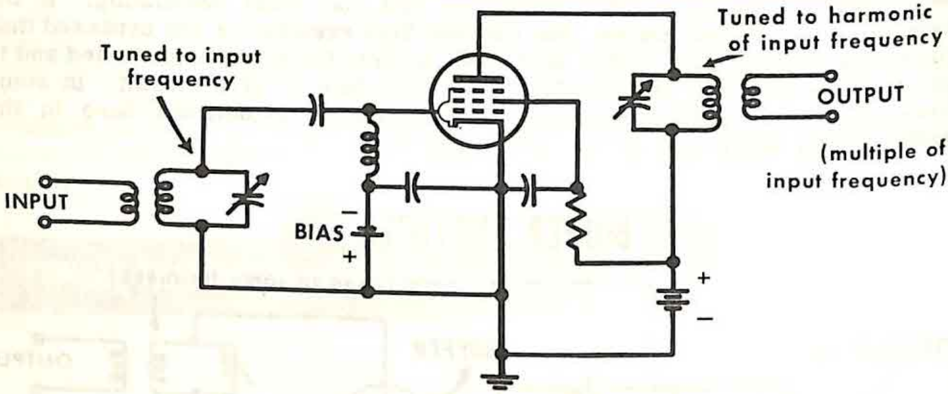


USING a BUFFER AMPLIFIER for ISOLATION


Changes in this stage will not affect operation of this stage
OSCILLATOR
BUFFER
AMPLIFIER
POWER
AMPLIFIER

Frequency Multipliers


FREQUENCY MULTIPLICATION


Tuned to input frequency
INPUT
BIAS
−
+
Tuned to harmonic of input frequency
OUTPUT
(multiple of input frequency)
+
−

Frequency Multiplier

At the higher frequencies, oscillator frequency stability becomes difficult to maintain. Hence, it has been found best to keep the oscillator stage operating at a lower frequency, while arriving at the desired frequency by frequency multiplying. If the plate-tank circuit of the buffer amplifier is tuned to the second harmonic of the driving signal applied to the grid, the stage becomes a frequency doubler and the output voltage has a frequency equal to twice that of the input. Likewise, the buffer amplifier may become a tripler or a quadrupler. Where a greater amount of frequency multiplication is desired, two or more stages of frequency multiplication are operated in cascade.

The output of a frequency multiplier is a harmonic of the input signal. The harmonic output of a class-C amplifier can be controlled by controlling the value of the peak plate current. The harmonic output increases at first, as the width of the plate current pulse is decreased, but will then start to decrease as the pulse width is decreased still further.

Frequency-Multiplier Amplifiers

To act as a doubler, the plate-tank circuit must be tuned to twice the input frequency. As shown, following the plate-current pulse, the circulating current of the tank will carry the oscillations through two complete cycles before the next reinforcing plate-current pulse. With plate-current pulses applied at every other cycle, the output power available when operating as a doubler will be approximately one-half of that available when the amplifier is operated straight through.

OPERATION of a FREQUENCY DOUBLER

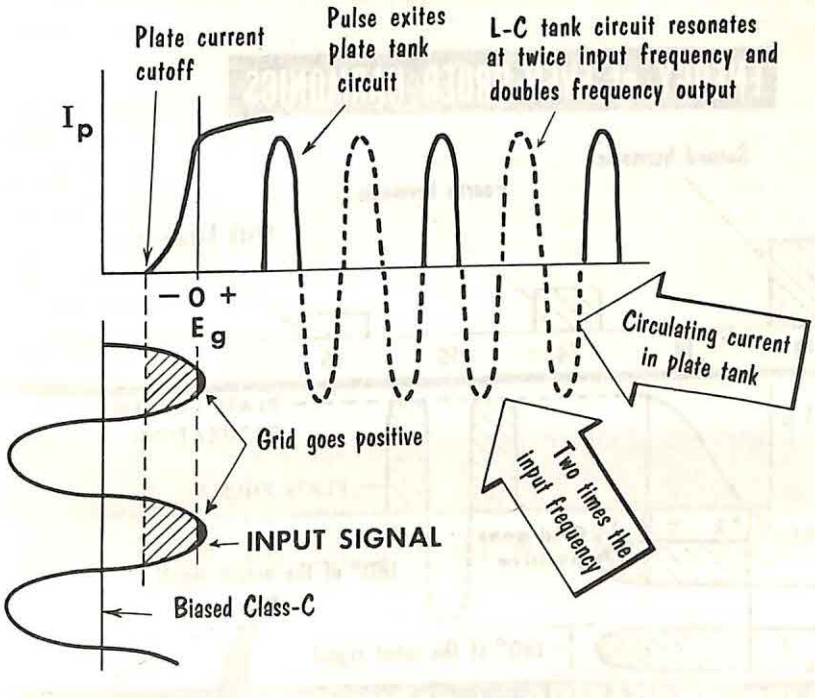


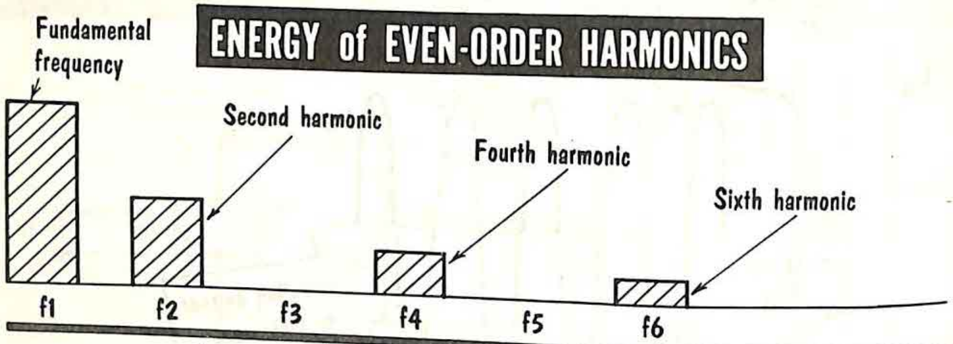
Plate current cutoff
Pulse exites plate tank circuit
L-C tank circuit resonates at twice input frequency and doubles frequency output
I_p
$-\ 0\ +$
E_g
Circulating current in plate tank
Grid goes positive
Two times the input frequency
INPUT SIGNAL
Biased Class-C

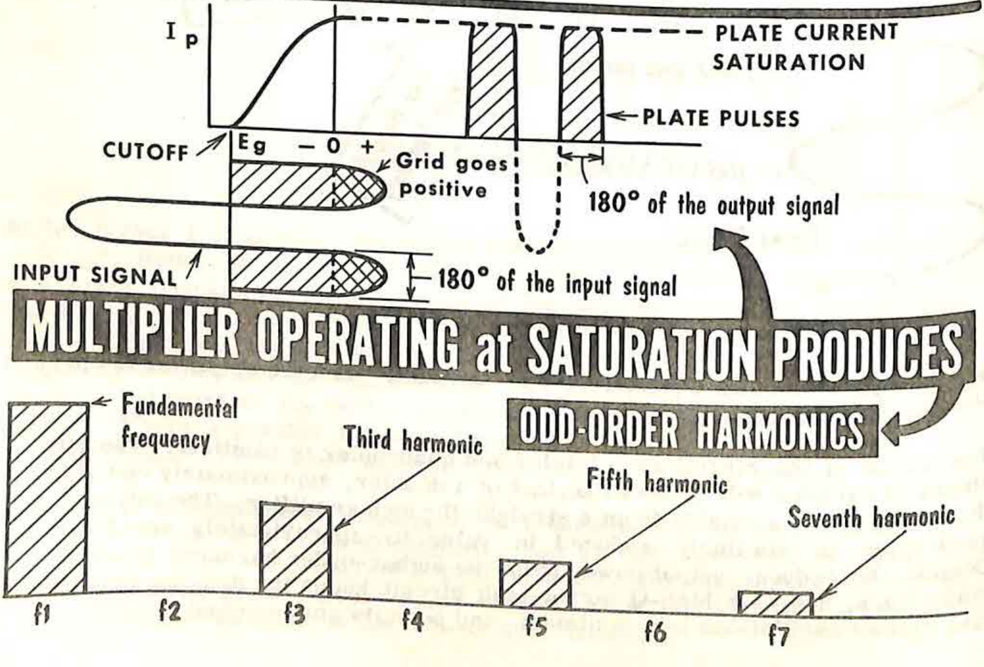
The action of the circuit as a tripler and quadrupler is identical. The efficiency of a tripler will be less than that of a doubler, approximately one-third the output power available from a straight-through amplifier. The output of a quadrupler is similarly reduced in value to approximately one-fourth. Despite the reduced output power from the higher-order harmonic frequency multipliers, use of a high-Q output-tank circuit keeps the damping of plate-tank circuit oscillations to a minimum, and permits ample output power.

Frequency-Multiplier Amplifiers (Contd.)

When even-order harmonics are produced, the second harmonic contains approximately one-half the energy contained in the fundamental frequency, with the fourth and sixth harmonics proportionally reduced. Circuits designed to produce even-order harmonics will not generate odd-order harmonics.

Odd-order harmonics can be produced by application of sufficient bias and signal level to cause plate current saturation and "square" the input signal. Assuming plate current conduction for 180° of the input cycle, there will be output pulse energy present at various odd-order harmonics of the fundamental frequency. As shown, the third harmonic contains approximately one-half the energy contained in the fundamental frequency, with the fifth and seventh harmonics proportionally reduced. A circuit operating with the bias set as shown, provides an excellent frequency tripler.





Diode Harmonic Generator

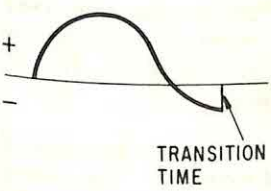
A solid-state frequency multiplier circuit using a special "step-recovery" diode is illustrated below. Action of the step-recovery diode upon a sine wave is shown; note that the negative alternation is not cut off; current continues to flow for a short time, then suddenly the current flow "snaps off" to zero. This snap off action, also called "step-recovery," is the source of the various names used to describe the special diode: step-recovery, snap-off, or snap diode.

The alternation that applies reverse-bias to the diode causes the minority carriers of the P and N material to be trapped. In their flow back to the junction, the minority carriers momentarily maintain current flow. As the minority carriers reach the junction, the current flow suddenly ceases, causing the steep curve shown (referred to as "transition time"). The near straight line square wave shape of the transition time indicates a high harmonic frequency content. (A square wave is a combination of many odd sine wave frequencies.)

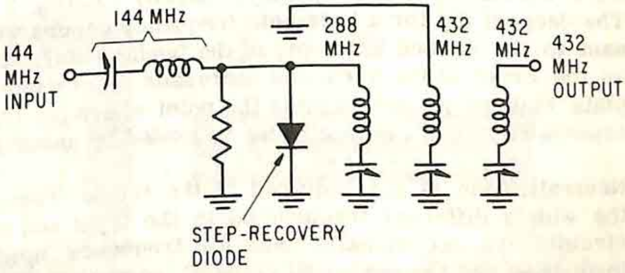
In the "tripler" circuit shown, the input frequency is 144 MHz, and the output, 432 MHz, is three times the frequency of the input. The input circuit to the diode is tuned to 144 MHz with the output of the diode tuned to 288 MHz to form a "doubler." The 288 MHz tuned circuit will also contain components of the 144 MHz frequency to provide a third harmonic content that will maintain oscillation in the isolated 432 MHz tuned circuit. Inductive coupling from the isolated tuned circuit to another circuit tuned to 432 MHz provides the output signal.

The loss of the tripler circuit shown is approximately 40%, i.e., a 10 watt input signal will provide approximately 6 watts at the output.

FREQUENCY MULTIPLIER WITH STEP-RECOVERY DIODE

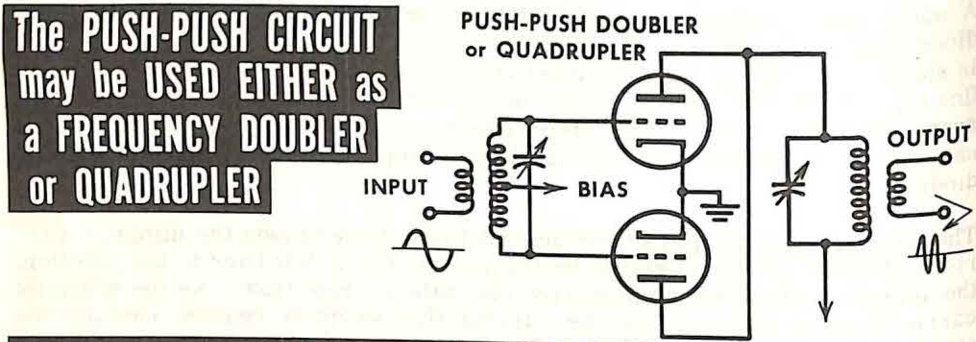


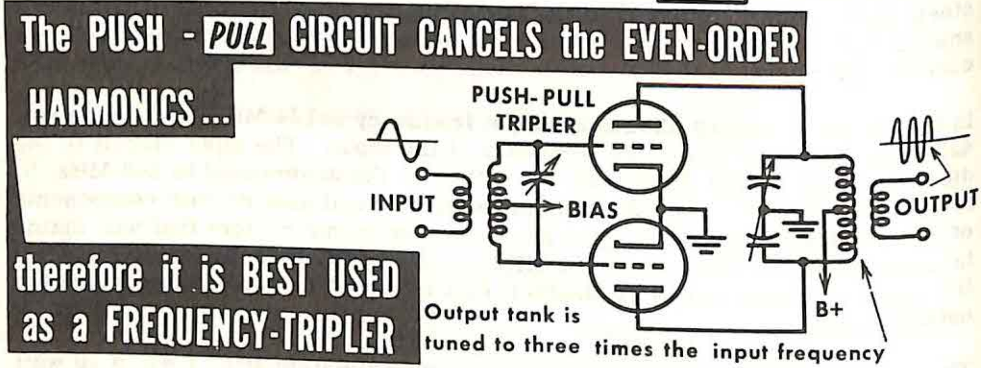
Step Recovery Diode Action



Tripler Circuit

Tuning Frequency Multipliers


The PUSH-PUSH CIRCUIT may be USED EITHER as a FREQUENCY DOUBLER or QUADRUPLER


The PUSH - PULL CIRCUIT CANCELS the EVEN-ORDER HARMONICS ... therefore it is BEST USED as a FREQUENCY-TRIPLER

Output tank is tuned to three times the input frequency

Plate current pulses in the frequency multiplier are usually of much shorter duration than in the conventional class-C amplifier. In this way the frequency content of the plate current pulses is enriched. The conduction angle in frequency doublers is about 110°-130°; in triplers 80-90°; and in quadruplers 60-70° of the input cycle. Tuning the frequency multiplier is like tuning the conventional class-C tuned r-f amplifier. Resonating the plate tank to a harmonic component of the plate current introduces a high impedance into the plate circuit at that frequency, thereby causing a fall (dip) in plate current. The deepest dip for a harmonic frequency occurs when the plate tank is resonant to the second harmonic of the fundamental. The dips become shallower as the order of the harmonic increases. Care must be taken when tuning the plate tank so as not to miss the point where the plate current falls. This is especially true if the multiplier is loaded by another stage.

Neutralization is not required in the triode-frequency multiplier because of the widely different frequencies in the input and output circuits. Two other circuits are occasionally used for frequency multiplication. They are the push-push and the push-pull class-C tuned amplifiers. The push-push circuit uses push-pull input and parallel connected output. The circuit is a predominantly even-order harmonic generator, hence is very useful as a doubler or quadrupler, especially the latter. The push-pull circuit eliminates even harmonics in the output, hence is a very efficient frequency tripler.

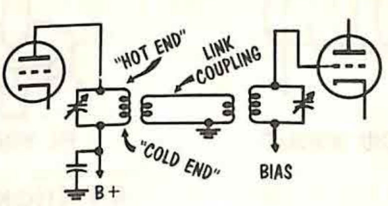
Interstage Coupling

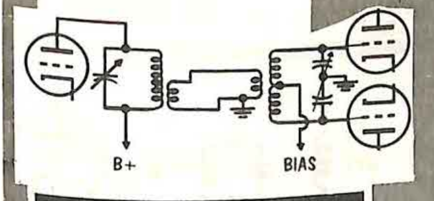
There are two main methods of coupling between stages of a transmitter – capacitive and inductive (transformer). Coupling is designed to provide the maximum transfer of energy with minimum loading. In capacitive coupling, also known as R-C coupling, the capacitor provides a low impedance path for the signal while simultaneously blocking the d-c plate voltage. To obtain a better impedance match the capacitor may be placed at various positions, or tapped down the coil. Inductive or transformer coupling consists of using the primary as the plate-tank coil, and the secondary as the grid coil for the next stage. The closeness of the coils determines the degree of coupling, and therefore the loading. The positions of the coils relative to each other also changes the degree of coupling. When parallel to each other, the coupling is maximum; when placed at right angles coupling is minimum. Coupling is unity or perfect when the coils are wound so that the wires are interwound. Then the tuning of the plate circuit also tunes the grid circuit.

In another form of inductive coupling, known as link coupling, a coil is connected at each end of the transmission line, and serves to link two tuned circuits. Long distances are permitted between the coils, since the transmission line impedance is low. The closeness of each coupling may be varied. The r-f signal developed across both the plate and the grid coils finds the top ends hot with respect to the bottom end which is cold (being at r-f ground). The best place to couple to the tuning coils is at the cold ends to prevent r-f voltage arcing. To keep developed harmonics to a minimum, one end of the link is grounded. This also reduces capacitance coupling between the tuned circuits.

In push-pull or balanced circuits, the centertap is the coil coupling point. Link coupling is also of advantage when coupling is required from an unbalanced to a balanced circuit.

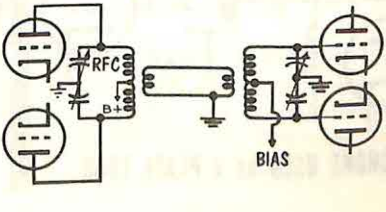
LINK COUPLING of TWO CIRCUITS





LINK COUPLING an UNBALANCED to a BALANCED CIRCUIT

LINK COUPLING TWO BALANCED CIRCUITS



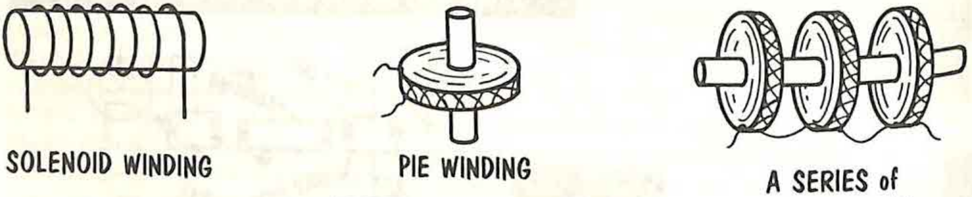
Interstage Coupling (Cont'd)

Since the action of impedance coupling is so dependent upon the use of r-f chokes, it is worth discussing them separately.

R-f chokes are a special form of inductance, usually consisting of many turns of fine wire wound either as a single coil, called a solenoid, or in a layer, called a pie winding, or a series of interconnected pie windings. They are specifically designed to have the least amount of possible stray capacitance between the windings. Every r-f choke has one frequency at which the value of inductance will resonate with the stray capacitance. This frequency should be much lower, or much higher than the frequency of the circuit in which it is placed. Some r-f chokes are designed to be used over a wide range of frequencies. Care must be taken with these chokes to see that nowhere in the range of frequencies used will there be a frequency that is resonant with the stray capacitance. Also, sufficient reactance must be offered at all frequencies. The higher the frequency, the higher the value of X_L with a given value of choke. This means that at high frequencies it is easy to obtain a large value of reactance, and therefore high-frequency r-f chokes usually contain only a small number of turns. The size of the wire used to wind the choke will determine how much current it can handle safely.

Using the r-f choke as a plate load, the entire signal is coupled through a capacitor to the tuned-input circuit. To vary the coupling the tap on the input coil is varied.

To vary the tap on the plate coil of a tank circuit, exposure to the d-c plate voltage becomes unavoidable. By using the r-f choke to provide a parallel path for the application of the B plus voltage, a parallel plate-feed circuit is obtained, freeing the tank circuit of the d-c plate voltage.

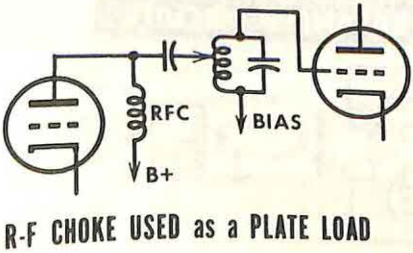


SOLENOID WINDING

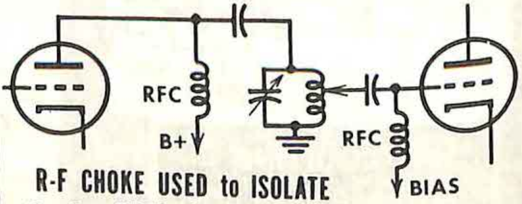
PIE WINDING

A SERIES of PIE WINDINGS

R-F CHOKES (RFC)



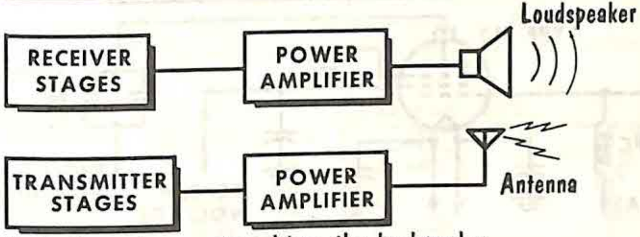
R-F CHOKE USED as a PLATE LOAD



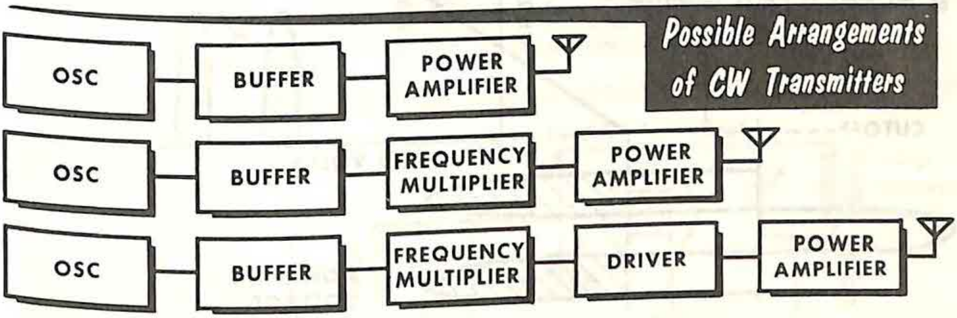
R-F CHOKE USED to ISOLATE the B+ FROM the TANK CIRCUIT, allowing safe handling of the tap

The Tuned R-F Amplifier and Driver Stage

The FINAL STAGE of a TRANSMITTER is the POWER AMPLIFIER



Just as the final stage of a receiver drives the loudspeaker, the final stage of a transmitter drives the antenna

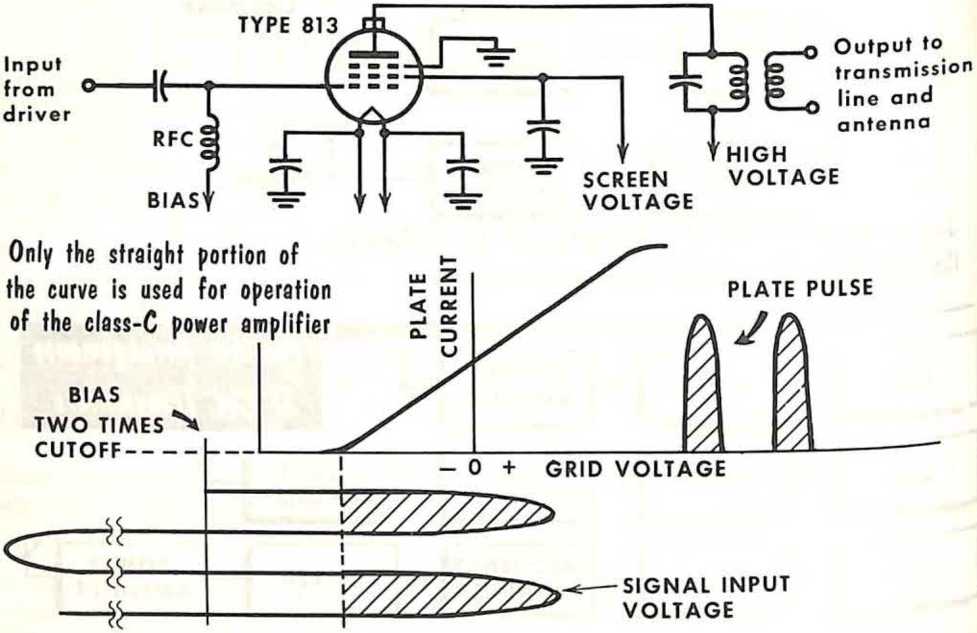


The r-f power amplifier, sometimes referred to as the "final," is a Class-C tuned amplifier. It is the last stage in the chain of amplification between the oscillator and the antenna. A transmitter may or may not include the buffer amplifier and frequency multipliers, but every transmitter, regardless of the kind of intelligence that it processes, contains an r-f power-amplifier stage. Sometimes the input signal required by the power amplifier is greater than that which might be obtained from a buffer stage or from a frequency multiplier. In this event a driver stage is used ahead of the power amplifier. The driver stage is generally a straight-through amplifier, i.e., the tuned circuit in its plate circuit is resonated to the frequency of the signal fed to the control grid of the same stage. In almost all respects the driver stage is a low-power version of the r-f power amplifier, differing from the latter mainly in the amplitude of the signal it processes, and in the lower values of grid bias and plate voltages used. While all transmitters contain a power amplifier stage, the amplifiers are not identical in all cases. They differ in the type of tube used to satisfy the output-signal power requirements, and in the operating voltages made necessary by the type of tube.

Several organizations of continuous wave (CW) transmitters are shown in block diagram form on this page. The relationship of the power amplifier to the rest of the circuit is readily apparent in each system. For ease of understanding, the keying method is omitted, as are the sources of operating voltages. They are dealt with later.

The Tuned R-F Power Amplifier

THE POWER AMPLIFIER



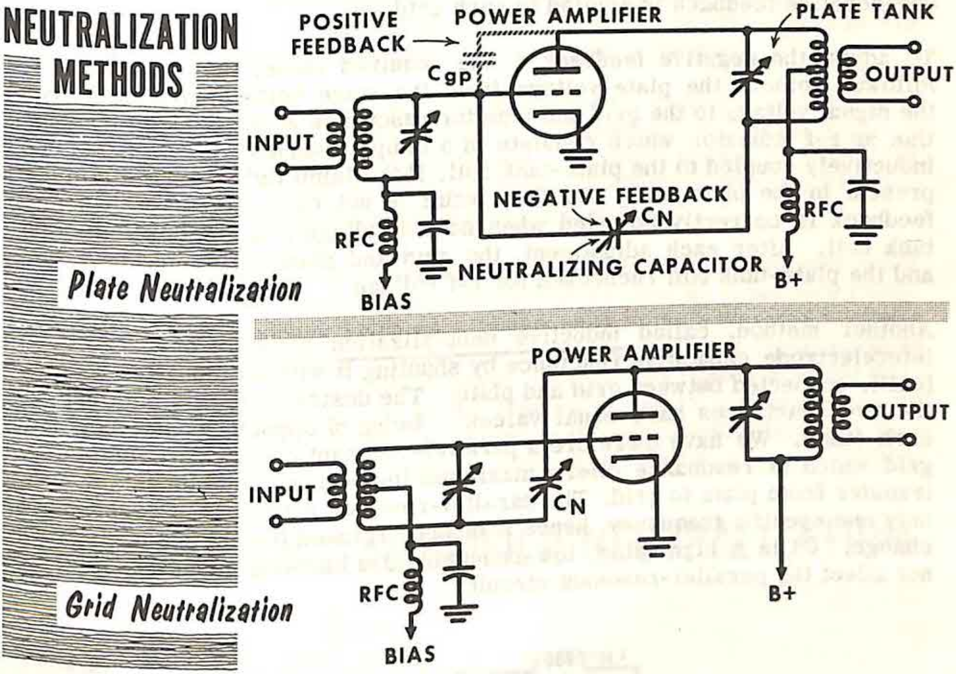
Only the straight portion of the curve is used for operation of the class-C power amplifier

The basic operating conditions for the Class-C tuned r-f amplifier have been described, but several qualifications pertinent to the power amplifier must be emphasized. First, is the requirement that the grid bias and plate voltage values be such that the changes in plate current for any given input-signal voltage occur along the straight portion only of the grid voltage-plate current characteristic. The plate current should rise from zero to maximum, but the maximum should not be beyond the saturation level, which as you will remember, was the maximum current condition in the Class-C frequency multiplier. The abovementioned restriction establishes a limit on the peak amplitude of the input-signal voltage. Limiting the plate current in this way reduces the amplitudes of the harmonics in the plate current, thereby minimizing the possibility of delivering harmonic frequency signals to the antenna.

Another consideration is that the stage from which the power amplifier derives its input-signal voltage must be capable of supplying the necessary power consumed in the power-amplifier grid circuit (input signal voltage × grid current) during the operating cycle of the plate current. R-f power amplifier tubes bear input power ratings for full output, as for example, "8 watts driving power." The stage ahead of the power amplifier should be capable of delivering more than the stated minimum input power requirement of the amplifier stage. In this way adequate grid drive is available when the amplifier is delivering full output.

Neutralization

In circuits such as buffers, drivers, and power amplifiers where both the input and the output frequency are identical, an acute problem exists. The positive feedback through the grid-to-plate interelectrode capacitance may cause oscillations. The higher the frequency the more acute the problem becomes. In low-power tetrode and pentode circuits, the problem still exists due to the high signal voltage. In spite of the low interelectrode capacitance, the small positive feedback may still be sufficient to start unwanted "parasitics," or oscillations. To prevent them, the simplest method, called neutralization, is to counter or "neutralize" with an equal amount of negative feedback.



One method, called plate neutralization, uses a neutralizing capacitor the purpose of which is to obtain the correct amount of negative feedback, and to apply it to the grid in the proper phase. For this purpose we connect the centertap of the plate r-f coil to ground. This makes the bottom end of the tank coil "hot" and of opposite polarity from the top of the coil, and suitable for application of a negative feedback voltage. Hence, the negative feedback is obtained from the end of the coil opposite to the plate.

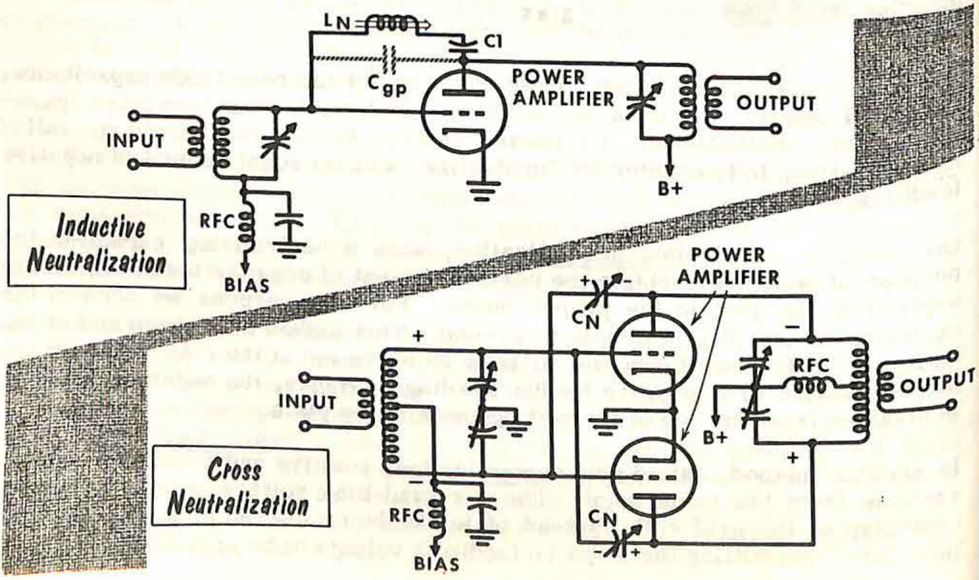
In another method, called grid neutralization, positive and negative feedback emanate from the same point. The d-c grid-bias voltage is applied to the centertap of the grid coil, instead of to the bottom of the grid coil which is now "hot," permitting the negative feedback voltage to be applied there.

Neutralization (Cont'd)

For balanced circuits, cross neutralization is used. Portions of the output voltage of each plate are coupled to the grid of the opposite tube. Assume that at a given instant the signal voltage across the grid coil appears with the voltage shown, and which in turn places a voltage of opposite polarity on the output coil. The charge on the plate side of the neutralizing capacitors causes the opposite plate on the grid side to have an opposite charge. Hence, degenerative feedback is applied to each grid.

To adjust the negative feedback to the required value, the procedure is as follows: remove the plate voltage from the stage being neutralized. Apply the signal voltage to the grid and tune for resonance at the desired frequency. Use an r-f indicator which consists of a lamp in series with a turn of wire, inductively coupled to the plate-tank coil. If the lamp lights, an r-f voltage is present in the plate tank, and the circuit is not neutralized. The negative feedback is correctly adjusted when no r-f voltage is indicated in the plate-tank coil. After each adjustment, the grid and plate coils must be retuned, and the plate-tank coil rechecked for r-f voltage.

Another method, called inductive neutralization consists of canceling the interelectrode capacitive reactance by shunting it with an inductive reactance (coil), connected between grid and plate. The desired effect is obtained when the two reactances have equal values. Being of opposite phase they cancel each other. We have therefore a parallel-resonant circuit between plate and grid which at resonance offers maximum impedance, and blocks any energy transfer from plate to grid. The parallel-resonant circuit is at resonance for only one specific frequency, hence it must be retuned for any signal frequency change. C1 is a high value, low-reactance d-c blocking capacitor, and does not affect the parallel-resonant circuit.



Inductive Neutralization

Cross Neutralization

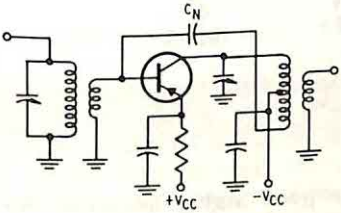
Transistor R-F Amplifier Neutralization

Transistor junction capacitance can provide a feedback path from the output to the input causing undesired oscillation. Controlled feedback (neutralization) for transistor r-f amplifiers is similar to that used in tube r-f amplifiers. In the circuit shown the -V_{CC} tap is essentially the end of the tank circuit coil (this is the result of the bypass capacitor providing an r-f ground at this point). The additional turns provide the out-of-phase feedback that is coupled to the input via C_N. In place of the added turns, the feedback may be taken from the coupled signal driving the succeeding stage. This removes the collector coil feedback winding; however, a larger value of C_N must be used.

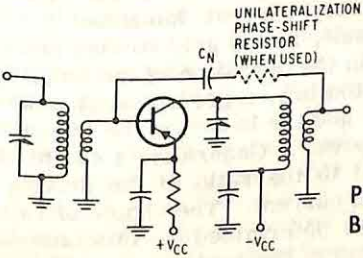
The neutralized circuits shown are typically used for frequencies ranging up to approximately 50 MHz. Above these frequencies special transistors or specially designed circuits (including careful component layout) must be used. Essentially, this is a result of the wide frequency changes creating wide impedance changes that make feedback circuits inoperative.

The changing impedances noted above are caused by the fact that part of the junction feedback path contains resistive paths as well as capacitive paths. The resulting r-c feedback imparts a phase shift to the undesired feedback signal that cannot be completely overcome by the neutralizing signal because they are out-of-phase. The out-of-phase neutralizing feedback signal does prevent undesired oscillations, but at the expense of greatly reduced gain. To overcome this problem, a resistor is placed in the neutralizing feedback signal path to provide an offsetting r-c phase shift; this is called unilateralization.

TRANSISTOR R-F AMPLIFIER NEUTRALIZATION



Utilizing Feedback Turns to Provide a Neutralizing Signal

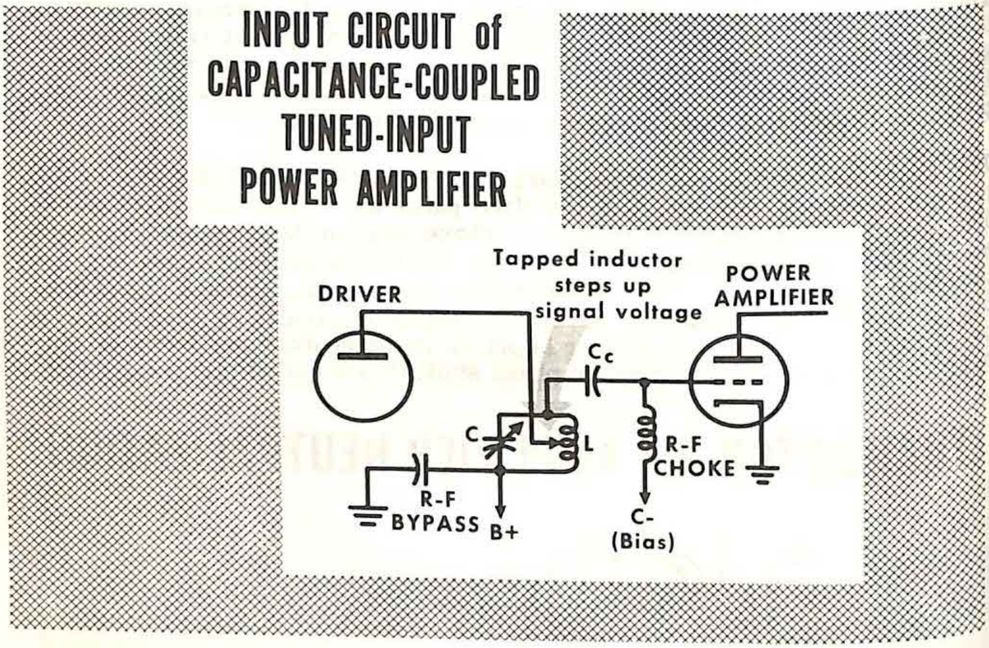


Providing Feedback from the Base Circuit of the Succeeding Stage

Power-Amplifier Input Circuits

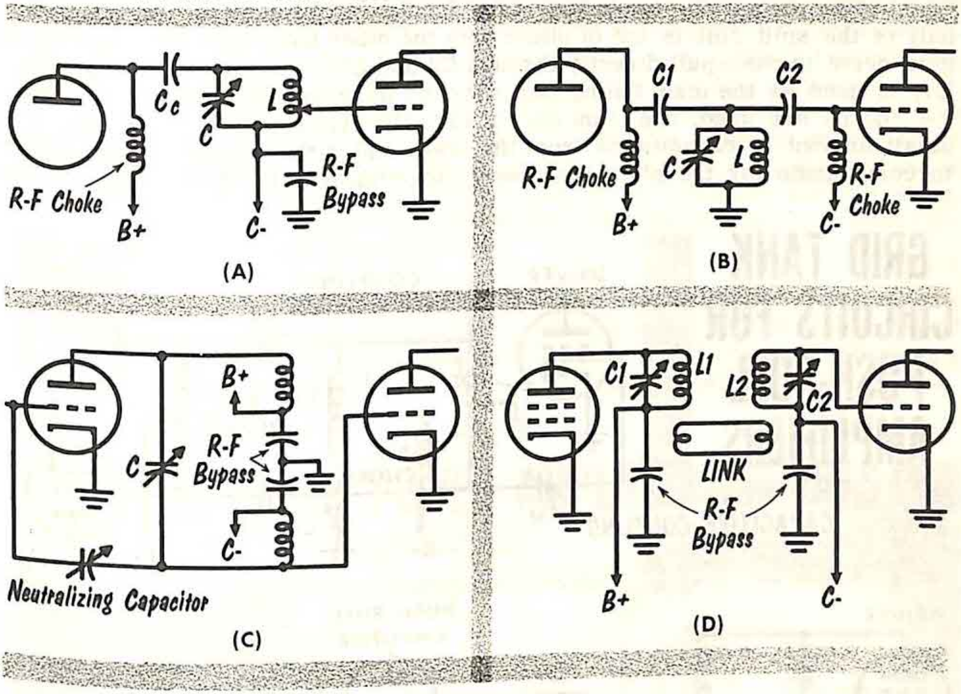
It is highly desirable to have as efficient a transfer of power from the driver stage to the power amplifier as possible. Therefore, the grid tank circuit must provide an impedance match between the grid input impedance of the amplifier and the plate output impedance of the driver stage. If a grounded-grid amplifier is used, similar considerations apply to the cathode tank circuit.

The impedance of a circuit normally is defined as the ratio of voltage to current. However, in the grid-circuit of a class-C amplifier, this ratio is far from constant. When the grid voltage goes highly negative, no current is drawn at all; when it is positive, a great deal of current flows. Therefore, the impedance of the grid circuit varies over a range from an extremely high to an extremely low value through the operating cycle. If the input impedance of the grid circuit is too high, the heavy current demanded by the extreme grid swing cannot be drawn. As a result, actual grid voltage and consequent loss of peak efficiency are reduced in the operation of the amplifier. If the impedance of the grid tank circuit is too low, a great deal of power from the driver stage is required to operate it, and the losses in the inductor consume a considerable amount of the applied power. Generally, a compromise value is used which is approximately equal to the ratio of the driving power in watts divided by the square of the grid current. The choice of values for the components in the grid tank circuit is determined by this impedance. The result usually is satisfactory regulation of the grid voltage without excessive power loss.



INPUT CIRCUIT of CAPACITANCE-COUPLED TUNED-INPUT POWER AMPLIFIER

Power-Amplifier Input Circuits (Cont'd)



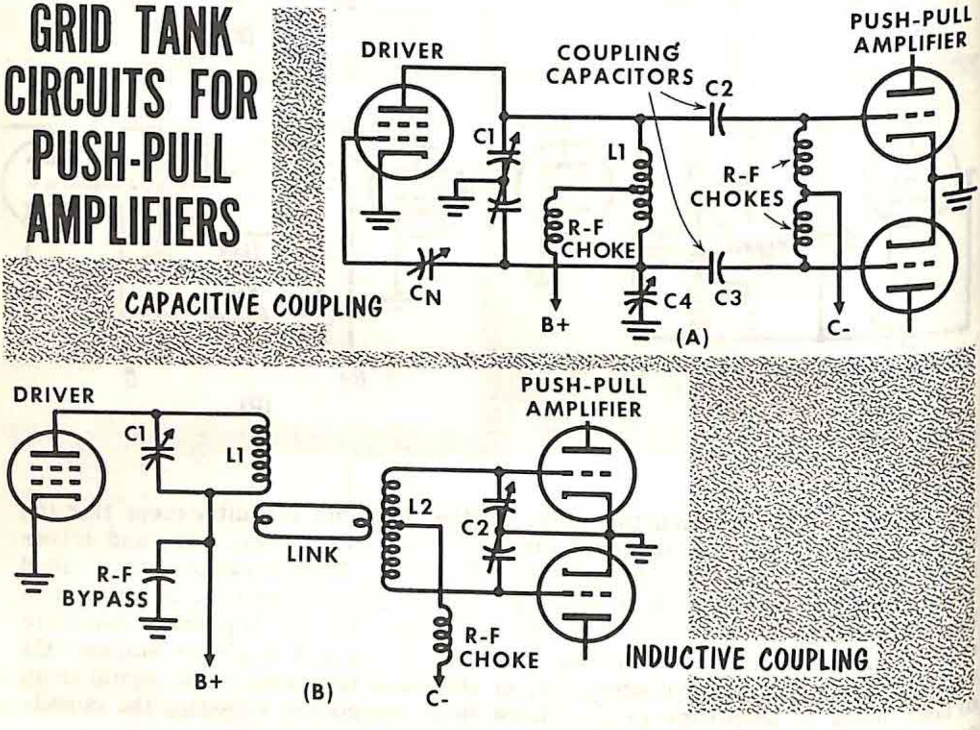
POWER AMPLIFIER GRID-TANK CIRCUITS

The circuit at A is much the same as the previous circuit except that the tuned circuit is now in the grid circuit of the power amplifier, and driver plate voltage is supplied through an r-f choke. This arrangement is used when the required impedance at the grid of the power amplifier is lower than the output impedance needed in the driver stage. Circuit B permits complete d-c isolation of the tuned circuit from the driver and amplifier stages. C1 and C2 block the d-c voltages, and at the same time couple the signal from driver plate to amplifier grid. There is no means for adjusting the impedance between grid and plate circuits.

Circuit C permits the driver to be neutralized to prevent oscillation. It also provides variable drive for the amplifier, and d-c isolation for the bias and high-voltage circuits without need for r-f chokes. Inductor L of the tuned circuit is split into two parts at the center, each of which is grounded separately with r-f bypass capacitors. Driver plate voltage thus cannot reach the amplifier grid. In circuit D the tuned-plate tank of the driver is inductively coupled through a low-impedance link to a tuned-grid circuit. The link inductance is small and therefore the impedance of the coupling circuit is low. This minimizes losses in the transmission of driving power, and provides great flexibility in matching impedances between the driver and power amplifier.

Input Circuits For Push-Pull Amplifiers

The input circuits for push-pull amplifiers are variations of those used in single-ended amplifiers. The capacitive coupling arrangement in A uses a tuned-plate circuit for the driver tube formed by L1 and C1. Because each half of the split coil is out of phase with the other half, each half can supply grid drive in push-pull directly through C2 and C3. A split-stator capacitor, C1, is used as the main tuning capacitor for the coupling arrangement. Two r-f chokes are used, one from each grid to the bias supply. C4 introduces a small amount of capacitance from the lower end of the tank circuit to ground to compensate for the plate-to-ground capacitance of the driver tube, which appears across the upper half of the circuit. Driver plate voltage is applied through an r-f choke. Neutralization of the driver stage is provided by C.



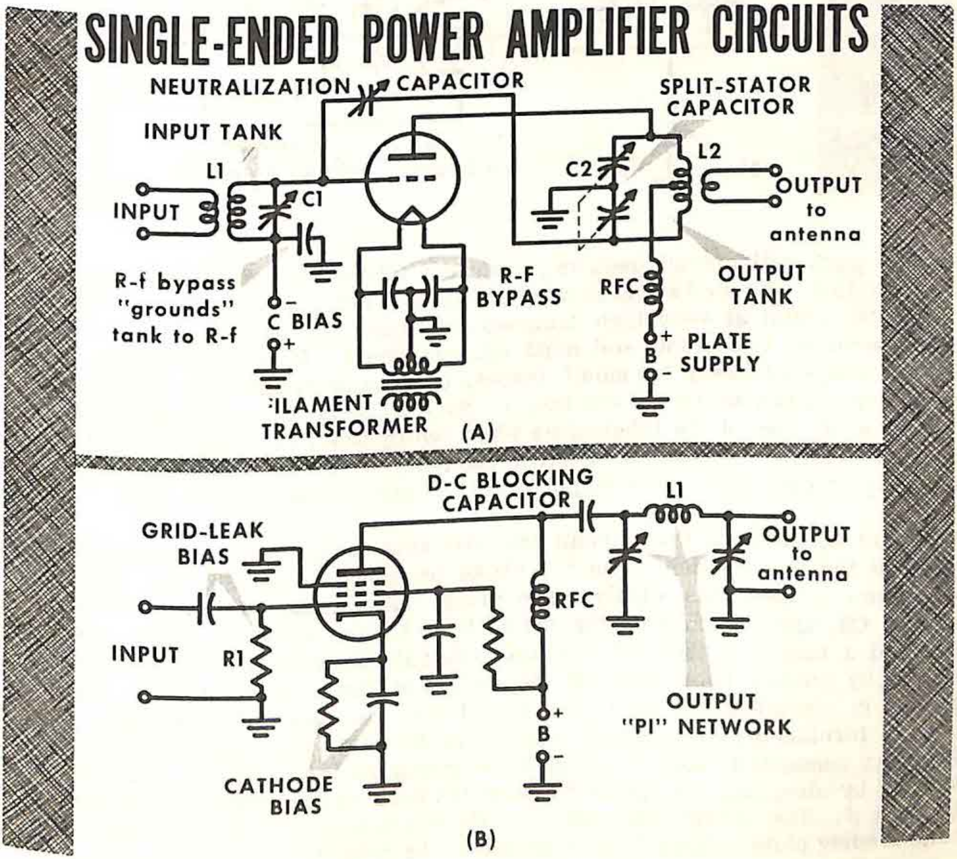
An inductive coupling arrangement for the grid tank circuit is shown in B. The link circuit transfers energy from the driver tank, L1-C1; out-of-phase voltages to the push-pull grids of the amplifier are developed across C2.

The choice of circuits depends on several considerations. Where the tuning capacitor is grounded directly, it must have twice the voltage rating of one grounded through a capacitor. In some instances, the use of an r-f choke for bias is undesirable. The link-coupled circuits permit the driver to be located at some distance from the amplifier and connected to it through a low-impedance transmission line.

Single-Ended Power Amplifiers

A power amplifier that uses one tube is called a single-ended circuit. The circuit is usually the same whether operated class-B or -C. The difference is in bias and excitation voltages and in component values. The single-ended circuit generates more harmonic output which sometimes is a disadvantage. It is however the simplest circuit to use over a wide range of frequencies. Several types of tank circuits provide a wide range of impedance matching. These circuits are necessary where a variety of different antennas must be used. In A, the plate tank is composed of a variable capacitor with a single rotor and two stators, and L2. The capacitor is called a split-stator, and is used to obtain the out-of-phase voltage that is fed back for neutralization. The output tank is coupled to the antenna by a link coil around L2. This circuit is popular with high-power triodes.

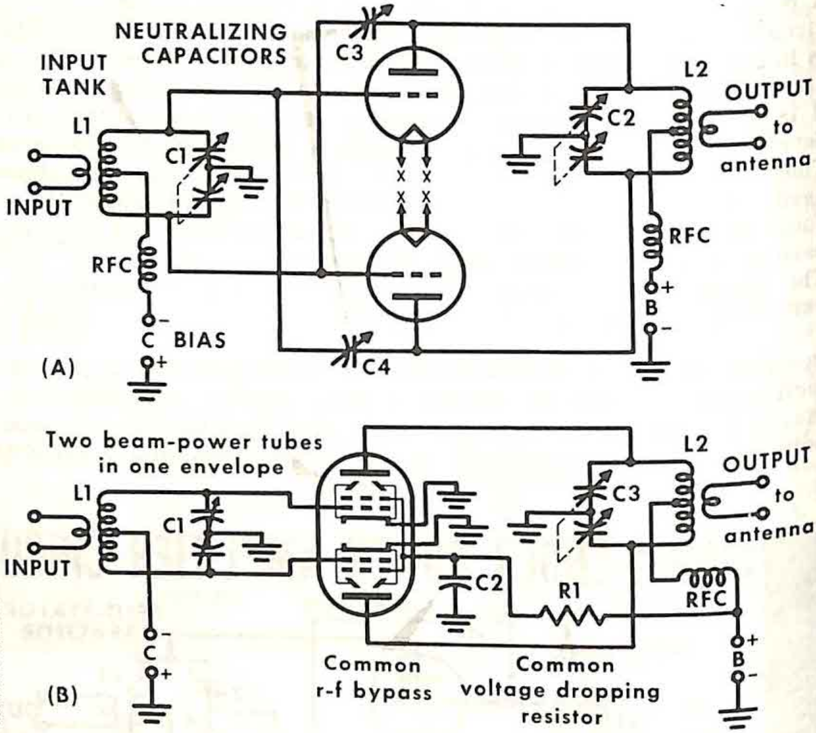
In circuit B, grid-leak bias is used. Cathode bias also is provided as a protective measure in case excitation fails, which would result in a loss of grid bias if R1 alone were used. The tank circuit is a special impedance-matching network known as a pi network. It can be used with almost any length antenna.



SINGLE-ENDED POWER AMPLIFIER CIRCUITS

Push-Pull Power Amplifiers

PUSH-PULL POWER AMPLIFIER CIRCUITS



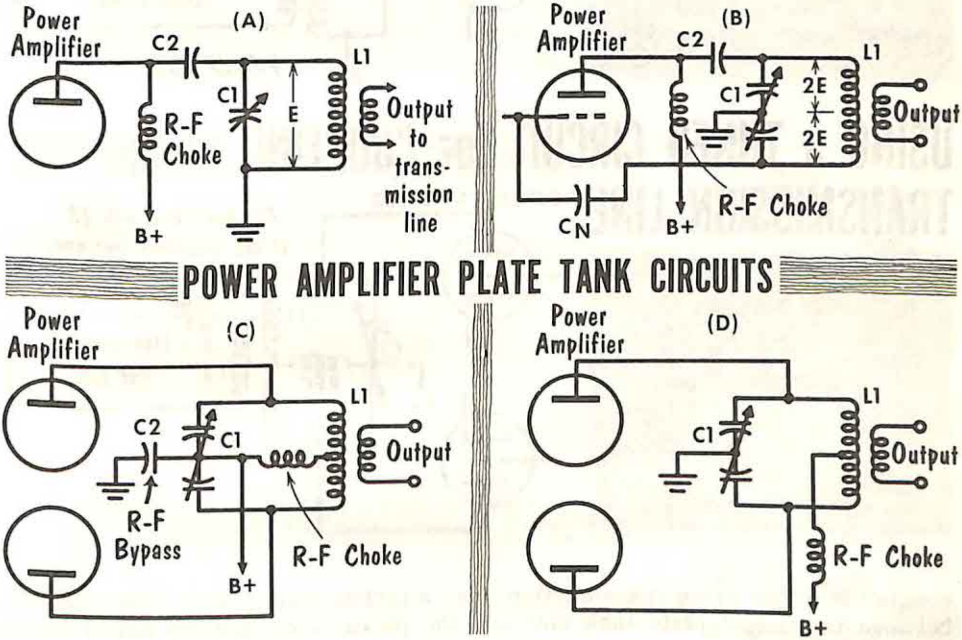
Since a push-pull circuit uses two identical tubes, advantage is sometimes taken of this, and the two tubes are combined in one glass envelope. This is especially useful at very high frequencies where the length of connecting leads becomes important, and must be kept short. Push-pull circuits have the advantage of lower harmonic output, ease of neutralization, and greater output for a given amount of excitation. Such a circuit requires only as much excitation as one of its tubes does when run by itself in a single-ended connection. This is because both halves of the grid-voltage cycle are used alternately by each tube. The output is recombined in the plate circuit.

In circuit A, the input tank circuit provides equal and opposite voltages to the grids of the two triodes. The r-f choke provides a means of inserting grid bias from a fixed bias supply. The plate tank is made with split-stator capacitor C2, and recombines the output from the two triodes. Since opposite sides of a tank are 180° out of phase, neutralizing voltages may be obtained simply by feeding back some of the energy at these points to the opposite grids. In circuit B the grid tank L1-C1 provides drive for the tube. Grid bias is furnished from a fixed supply. In the tube, the screens of both sections are connected, and C2 serves as a bypass for them. R1 provides screen voltage by dropping the plate voltage because of the current that passes through it. The output tank circuit is the same as in A. The r-f choke permits feeding plate voltage to both halves of the tube.

Power-Amplifier Output Circuits

A large variety of practical circuits has been devised which present the proper load impedance to the power amplifier when connected to the transmission line or antenna. The simple parallel-resonant tuned circuit in A is frequently used for single-ended tetrode amplifiers. The circuit is shunt-fed. Tank circuit C1-L1 is coupled to the plate by C2. The advantage of this circuit lies in the removal of all d-c voltages from the tuning capacitor. This means a lower value of total voltage across this component with corresponding smaller size. A major shock hazard from contact with an exposed portion of the tank circuit is removed, but possibility of a bad r-f burn always exists.

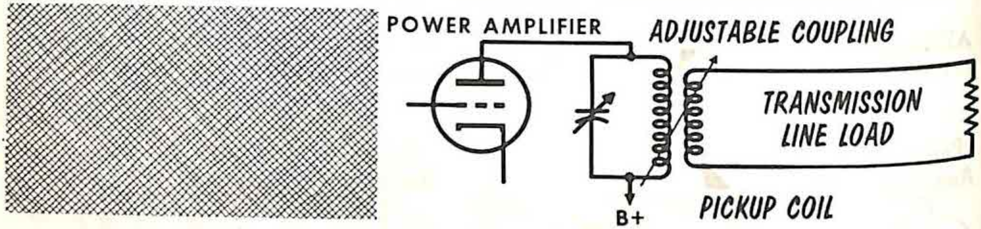
Although circuit A is satisfactory when used with tetrodes and grounded-grid triodes, it provides no means of neutralizing an ordinary grounded cathode triode. In B, C1 has a split-stator with the rotor directly grounded. This permits an out-of-phase voltage to be taken from the lower end of the coil and returned to the input through neutralizing capacitor C_N. The split-stator capacitor effectively divides the circuit in two parts, and an r-f peak of twice the d-c plate voltage can appear across each. This requires a physically large capacitor. The circuit in C is the push-pull counterpart of the simple resonant tank. A split-stator capacitor is used with the push-pull version, and the rotor is grounded for r-f through C2. To reduce the voltage across each half of C1, the plate voltage sometimes is connected to the rotor. The shock hazard introduced by this can be avoided by grounding the rotor of C1 directly (D), and applying the plate voltage through a choke.


POWER AMPLIFIER PLATE TANK CIRCUITS

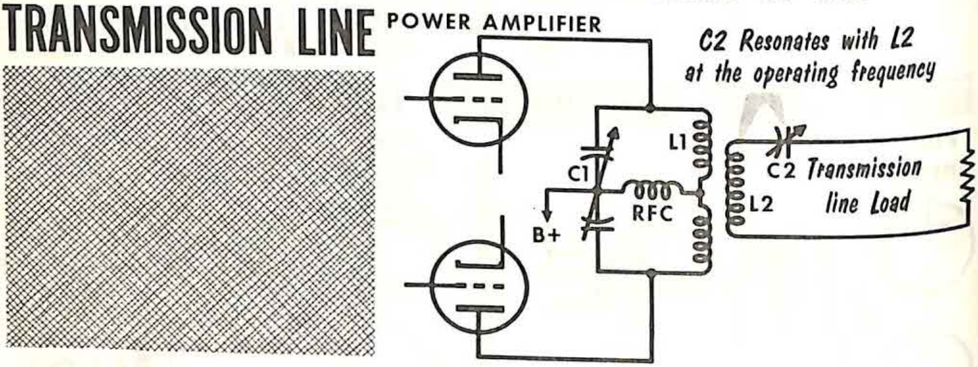
Output Coupling

The output of the final stage, or power output stage, has to be coupled to the transmission line as efficiently as possible to ensure maximum output to the antenna. A transmission line, to be discussed later, can be assumed for present purposes to appear as a pure resistive load, the value of which is determined by the characteristics of the type of transmission line used. To couple the output to the transmission line, a pickup coil is used. The coupling between the output plate-tank coil and the pickup coil is made adjustable to permit changes in loading.

COUPLING the OUTPUT to the TRANSMISSION LINE



USING a TUNED CIRCUIT for COUPLING to the TRANSMISSION LINE



The pickup coil acting as the source for the load represented by the transmission line should match the impedance of the transmission line for maximum transfer of power. This is not a simple thing to accomplish; a mismatch will often occur, which when reflected back to the output plate-tank circuit will cause it to be detuned. To overcome this obstacle a capacitor is placed in series with the pickup coil, providing a tuned circuit. Additionally the tuned circuit provides increased selectivity of the output frequencies, making it helpful in suppression of harmonics. The resonant circuit formed by the pickup coil and capacitor should not have too high a Q. If the output becomes too selective it will have to be retuned for each small change in output frequency.

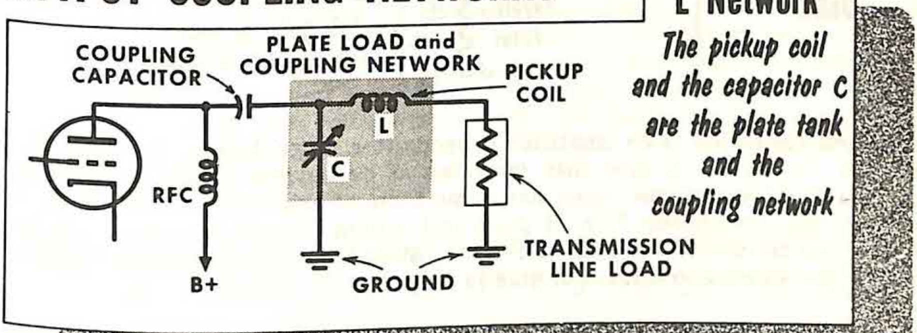
Output Coupling (Cont'd)

In place of the output tank circuit and transmission line tuned circuit, a network may be used which will act as both the tank circuit and matching circuit to the transmission line impedance. An L network uses an r-f choke for the plate load and a capacitor to couple the output to the tuning capacitor and inductance forming the L network. This places the transmission line impedance in series with the L and C of the tuned output circuit.

One of the most frequently encountered variable matching networks for the output of an r-f amplifier is the pi network. The plate voltage fed through the r-f choke is prevented from reaching the antenna by the coupling capacitor. The pi network of C1, L1, and C2 is capable of matching a wide range of impedances, and operates as a voltage divider. The combination of L1 and C2 forms the divider circuit which develops higher or lower voltages at the output terminal. C1 then tunes the combination of C2 and L1 to resonance at the operating frequency. Depending on the relative values of C1 and C2, a voltage much lower than the a-c plate voltage can be developed. Thus, this circuit can match an extremely wide range of impedances.

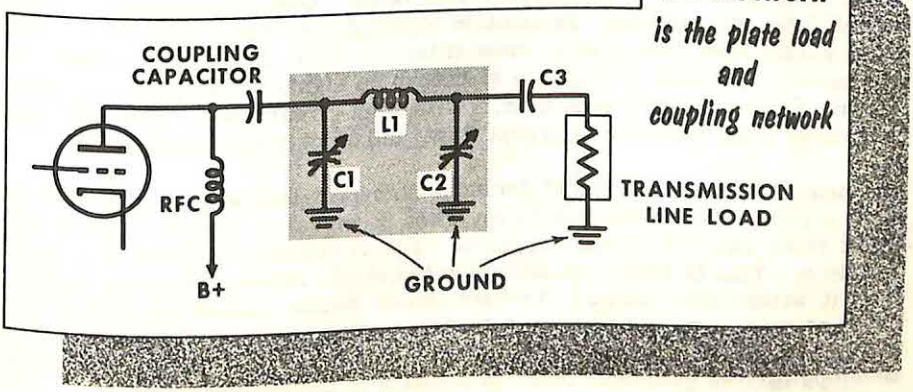
OUTPUT COUPLING NETWORKS

L Network



The pickup coil and the capacitor C are the plate tank and the coupling network

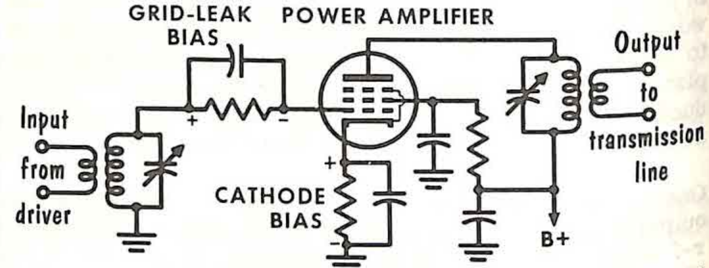
Pi Network



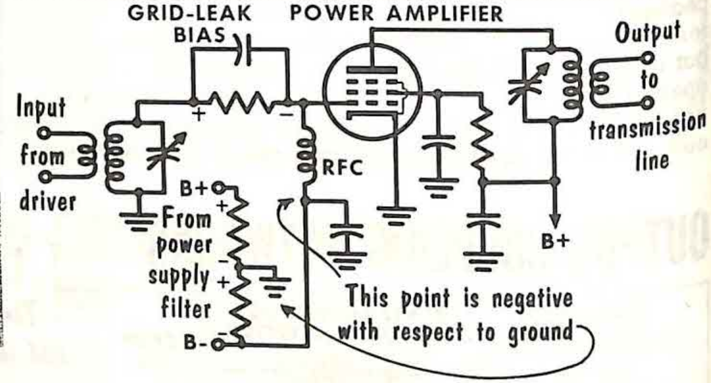
is the plate load and coupling network

Bias Voltages

COMBINING GRID-LEAK and CATHODE BIAS



COMBINING GRID-LEAK and POWER SUPPLY BIAS



The proper operation of an amplifier depends to a large degree upon the correct bias voltages. A tube that operates at or beyond cutoff, such as in class-B and -C operations, must use some form of external bias. In class-A operation, the continuous flow of plate and screen current through a cathode resistor can be used to develop self-bias. Most transmitter circuits operate class-C; therefore some form of bias is required.

Grid-leak bias develops a bias voltage due to the presence of a signal. Driving the grid positive draws grid current, develops a voltage drop across the grid resistor, and charges the capacitor. After several cycles, the charge on the grid levels off at the correct bias value. Loss of grid drive, however, causes loss of grid bias. In addition to accidental loss of grid drive, a condition exists when CW code is transmitted for short durations. Between "dots and dashes" the lack of signal is as though no signal were applied to the grid, causing a loss of grid-leak bias. With high-power tubes, the lack of bias may cause excessive plate current flow, and quickly ruin the tube.

A typical circuit shown, which includes both grid-leak and cathode bias, prevents excessive plate current flow. When no signal is applied to the grid, the heavy plate current flow through the cathode resistor develops a large voltage drop. This is sufficient self-bias to quickly reduce the plate current and keep it within safe limits. Another circuit shown makes use of a minimum value of bias voltage from an external source, such as the tap of a voltage divider or a separate bias supply. When the signal is applied, the grid drive develops its own grid-leak bias, in addition to the external bias.

Transmitter Meters

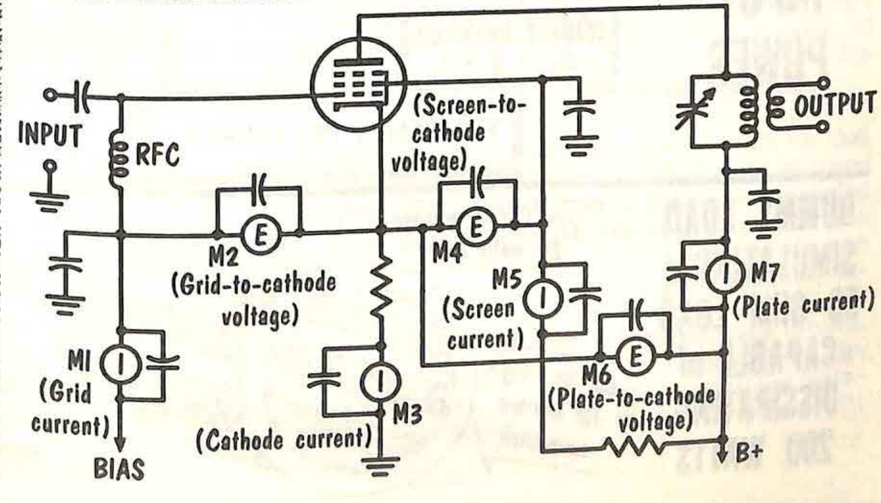
RUNNING-TIME METER

Metering performs a vital job in maintaining a transmitter. Metering the many voltages and currents ensures high performance, and indicates present or possible future troubles. In high-power, high-cost commercial transmitters, individual meter movements are generally used for each reading. In less complex transmitters, a single meter is used to monitor many readings by switching it into different circuits. When metering in r-f circuits a bypass capacitor is always placed directly across the meter terminals.

To measure the length of operation time of a transmitter, a "running time" meter is used. The running-time, or elapsed-time meter is essentially an electric clock that reads in hours and tenths of an hour as shown. The running-time meter is usually connected across the power transformer primary winding to measure the time duration that ac is applied to the transmitter. Occasionally an a-c meter is used to measure the filament voltage of a high-power tube, but mostly d-c voltages and currents are measured.

In the typical placement of individual meters shown, meter M1 indicates grid current flow. To measure the voltage from grid to cathode, meter M2 is used. The current meter M3 in the cathode circuit measures the combined control grid, screen grid, and plate currents. At times, a cathode-current meter is used in place of a plate-current meter. This eliminates the placing of a meter where high voltage is present. To obtain the plate current value, the control grid and the screen grid currents must be deducted from the cathode-current reading.

TYPICAL PLACEMENT of METERS in a TRANSMITTER CIRCUIT

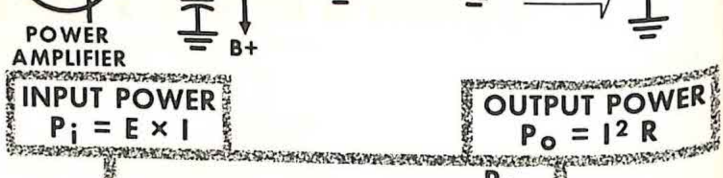


Output and Input Power

A transmitter is most often rated by its output power. To measure it, the transmission line is replaced with a dummy load that is a pure resistance of the same value as that of the transmission line it replaces. The dummy load's resistance must be capable of handling the dissipated heat. Many resistors may be placed in parallel; for example, placing ten 500-ohm resistors rated at 20 watts in parallel, provides a dummy load of 50 ohms, capable of dissipating 200 watts. In another method, the dummy load is immersed in oil and permits a still higher power dissipation. The true output power indication is obtained by measuring the actual watts of power being dissipated as heat in a resistor. A more accurate method of measuring heat dissipation uses a heat-measuring instrument called a calorimeter.

Most often, however, a thermocouple-type ammeter is inserted in series with the dummy load, as shown. The current indicated on the ammeter and the resistance offered by the load gives us the output power with the formula $P = I^2R$, where I is the measured current, and R the resistance of the load. The input-power rating of the final transmitter stage is obtained from the plate voltage (E) and plate current (I) values with the formula $P = E \times I$. Knowing both the input and the output powers of a final stage, its efficiency may readily be calculated.

MEASURING OUTPUT and INPUT POWER

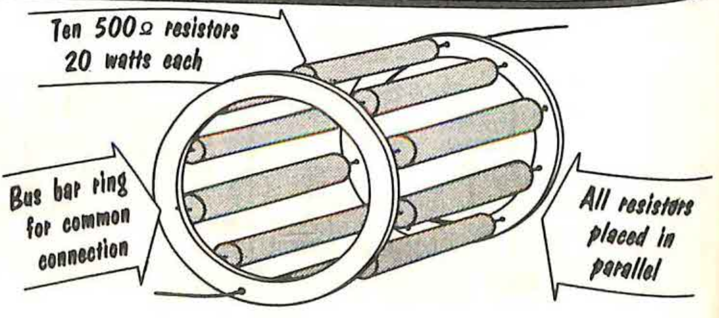


INPUT POWER
$P_i = E \times I$

OUTPUT POWER
$P_o = I^2 R$

$$\text{EFFICIENCY } (\%) = 100 \times \frac{P_o}{P_i}$$

DUMMY LOAD SIMULATING a 50-OHM LOAD CAPABLE of DISSIPATING 200 WATTS

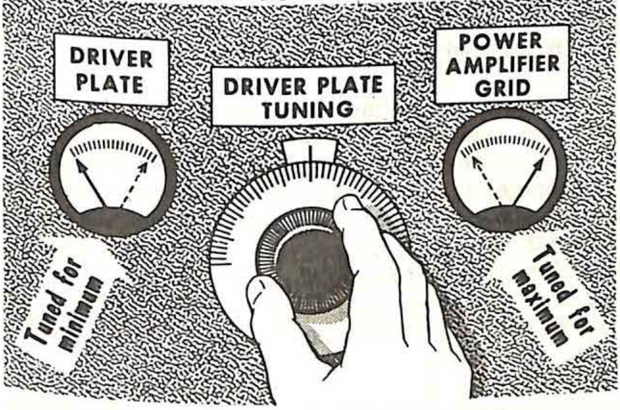

Ten 500Ω resistors 20 watts each
Bus bar ring for common connection
All resistors placed in parallel

Tuning Procedure

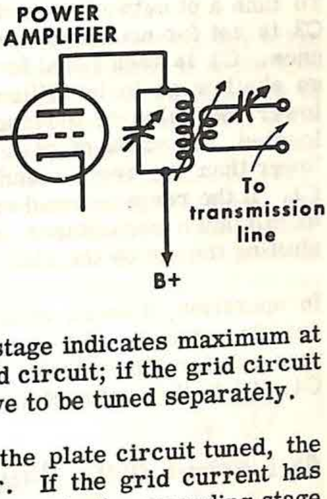
Assuming a correctly operating transmitter, the task of tuning it to the desired frequency can be difficult or easy, depending upon the skill of the operator. If the circuits are designed for it, it is best to start by removing plate voltage from all stages following the oscillator. The procedure generally is to tune the grid circuit first, then apply plate voltage and tune the plate circuit.

Tuning a driver output stage is shown. The plate circuit is tuned for a dip at resonance as indicated by a dip in the plate-current meter. At the same time the grid-current reading of the power-amplifier stage indicates maximum at the same point. This is true of a capacitor-coupled circuit; if the grid circuit of the following stage is a tuned circuit, it will have to be tuned separately.

TUNING A COUPLING STAGE



TUNING THE POWER OUTPUT STAGE



When plate and screen voltages are applied and the plate circuit tuned, the grid-current reading may become slightly lower. If the grid current has reduced to a value below that required, the coupling to the preceding stage should be increased to increase the grid drive. With the correct value of grid drive, and the grid circuit tuned, the plate circuit is then tuned for a dip at resonance. This procedure is followed for all stages except the final.

When tuning the power-output stage using a coupling circuit such as that shown, the following procedure is typical. The grid circuit should be tuned for maximum grid drive. The pickup coil of the transmission line is coupled approximately half way. With plate voltage applied, the tank circuit is then tuned for a dip at the resonant frequency. The tuning capacitor in series with the pickup coil is then adjusted for a maximum reading of plate current, indicating that the transmission pickup loop is tuned and drawing more energy from the output-tank circuit. This slightly detunes the output-tank circuit. This procedure is then repeated, the plate-tank capacitor retuned for a dip, and the pickup-coil tuning capacitor tuned for maximum, until the plate-current reading is set to the value recommended for the power-output tube being used.

Tuning Procedure (Cont'd)

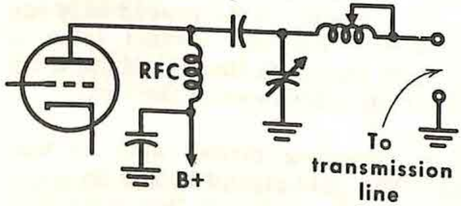
When tuning an L network such as that shown, the grid circuit, as in other circuits, should first be tuned for maximum grid drive. When tuning the output circuit it is possible to have a shallow plate-current dip, making it difficult to find. For a quick approximation the transmission line should if possible be temporarily shorted. With no load the plate-current dip at resonance will then be sharp and readily noticed.

With the short-circuit removed from the transmission line the value of plate current should then be noted. If the plate current is less than the recommended value the tap on the plate coil is moved to decrease the value of inductance. If the plate-current value noted is too high, the plate-coil tap should be moved to increase the value of inductance. Following any resetting of the plate-coil tap, the tuning capacitor should be readjusted for minimum plate current, and the grid circuit retuned for maximum grid drive.

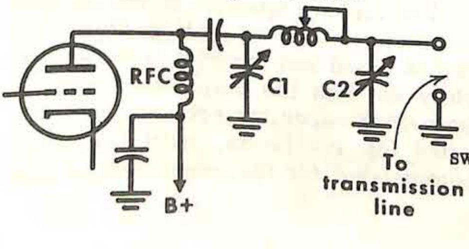
To tune a pi network output the grid circuit is tuned for maximum grid drive. C2 is set for maximum capacitance, and the coil is set for maximum inductance. C1 is then tuned for a dip in plate current. If the plate-current dip is so shallow as to be difficult to locate, the tap on the coil should be moved to lower the value of inductance by approximately one third. When the dip is located, the value of plate current should be noted. If the plate current is lower than the recommended value, reduce the capacitance of C2 and retune C1. If the recommended value of plate current is reached with C2 very close to minimum capacitance, a small amount of inductance should be added by shifting the tap on the plate coil.

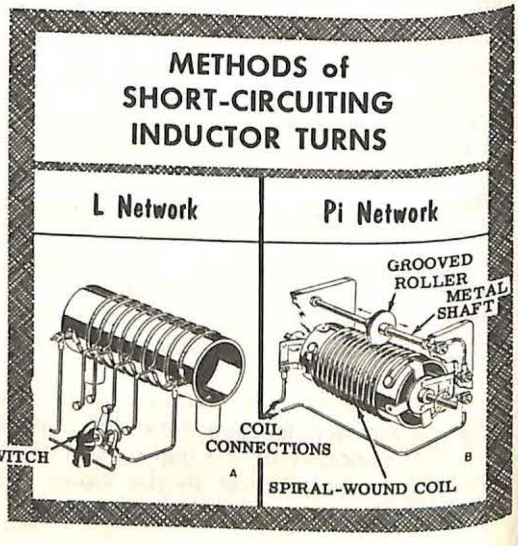
In operation, a small change of frequency may require that the pi network be quickly retuned. This is done by tuning C1 for a plate-current dip. C2 is then set for the correct value of plate current, causing a slight detuning of C1. C1 is then retuned for a plate-current dip.

An L Network Output Circuit

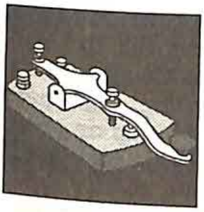


A Pi Network Output Circuit




METHODS of SHORT-CIRCUITING INDUCTOR TURNS

Keying

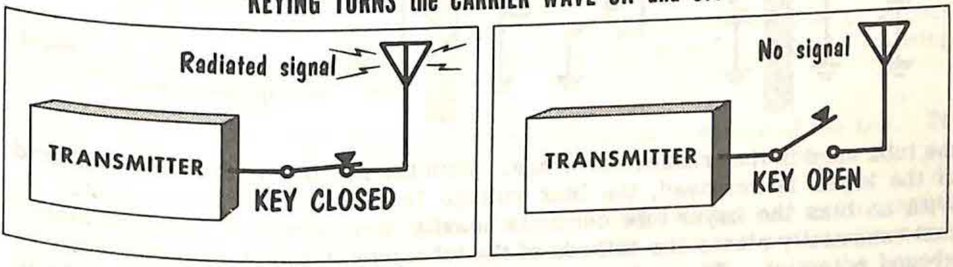


A TYPICAL KEY

The output signal of a transmitter using the various stages just described – oscillator, buffer, frequency multipliers and power output – would be continuous-wave type-A0 transmission. The output signal radiated from the antenna is called a carrier. To have the carrier convey information it is alternately turned on and off in the form of dots and dashes to transmit code characters. This type of interrupted transmission is called telegraphy, or type-A1 emission. To achieve telegraphy with a CW transmitter the ability to quickly and easily turn the carrier on and off must be placed somewhere in its circuitry. The instrument most often used to turn the transmitter signal on and off is the familiar telegraph key. Pressing the key down closes the contacts and turns the carrier on. By releasing the pressure upon the key a spring will return it to open, turning the carrier off. This is known as keying the carrier.

At first glance keying a transmitter appears simple, merely turning any stage on and off will cause the carrier to be on or off. Unfortunately it is not this simple; keying the transmitter requires careful thought and attention as to what stage should be keyed. In addition, keying a circuit brings with it attendant troubles. A typical example is a backwave. This consists of some carrier signal being transmitted when the transmitter output should be zero. The correct carrier signal is one that is fully on when the key is down, and zero when the key is up. Backwave caused by not having the transmitter completely off when the key is up will cause difficult and unpleasant reception for the receiving operator. When the carrier signal is turned on and off too sharply the rapid change in power level produces sidebands which are heard as clicks, called key clicks. The sharper the rise and fall of the carrier the wider the sidebands causing the key clicks, increasing their amplitude and possibly interfering with close-by signals. When the stage that is keyed is the oscillator, or a stage close to the oscillator, there is the possibility of a shift in frequency. This shift in frequency caused by keying produces a chirp when the key is pressed down, and another chirp when released. A change in oscillator frequency of only 25 hertz will cause sufficient chirp to make copying the signal unpleasant. A chirp of 200 hertz is enough to make copying extremely difficult.

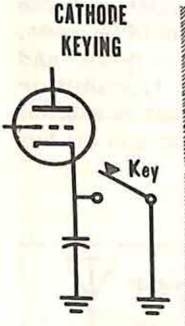
KEYING TURNS the CARRIER WAVE ON and OFF

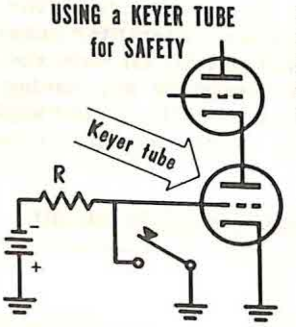


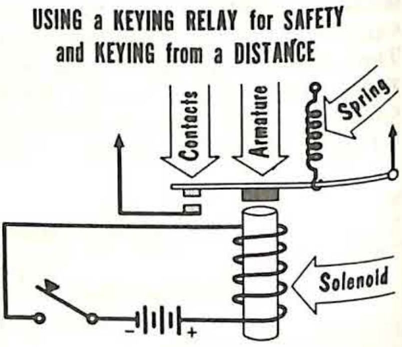
Keying (Cont'd)

The most frequent cause of backwave is keying in such a manner that the grid bias is not reduced beyond cutoff, permitting r-f energy to leak through and be amplified in succeeding stages. To eliminate this it is possible to key the oscillator stage directly. This, however, may result in chirping. Another method of combating backwave is to key the cathode circuit. The up or open key position opens both the plate circuit and grid return, blocking the grid and providing no plate current. Hence, no r-f signal is passed to the succeeding stage. Another possible cause of backwave is the keying of a circuit following the oscillator. This permits the oscillator to run continuously. If energy from the continuous-running oscillator leaks through to the antenna, a backwave may be generated. Careful shielding of the oscillator stage prevents this.

In low-power stages the voltage developed across the key may be safe; in high-power stages dangerous. To remove this danger an electronic switch can be substituted for the key, with the key controlling the switch. The circuit here shows vacuum-tube keying using a vacuum tube as an electronic switch. With the key in the up position the bias to the grid of the keyer tube keeps it cut off. The high-resistance open-keyer tube isolates the cathode of the tube used in the transmitter stage. With the key down the bias to the grid of the keyer is removed; the bias voltage is developed across resistor R. With no bias the keyer tube conducts heavily, providing low plate resistance that essentially places the cathode of the tube used in the transmitter stage at ground potential. The value of plate resistance of the keyer tube acts to place the plate of the keyer tube and the cathode of the transmitter tube at a slight positive potential; thus the keyer tube also acts as a cathode-bias resistor.







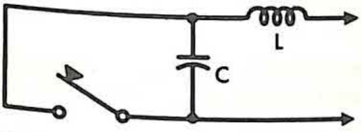
A method of keying any circuit where unsafe voltages may be present, is that of using a keying relay. When the key is closed the solenoid is energized, pulling the armature to it, closing the relay. Opening the key releases the armature and the contacts to open the circuit. A keying relay is quite useful for keying at long distances from the transmitter. The voltage used to energize the solenoid can be run for long distances in place of the cathode circuit or other circuit being keyed.

Keying (Cont'd)

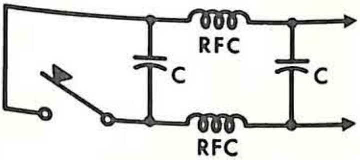
Eliminating key clicks requires a circuit that will cause a small time lag between the time the key is opened or closed, and the keyed circuit turned off or on. To do this, key-click filters are placed between the telegraph key and the circuit it is keying. A typical key-click filter which provides a time lag is shown. With the key closed the inductance in series with the circuit being keyed provides a lag in current flow by its reactance. This causes the keyed circuit to be turned on gradually. When the key is opened, the charge across C briefly continues the current flow, keeping the keyed circuit from being turned off too sharply.

BASIC KEY-CLICK FILTER

Produces time lag between time key is opened or closed and the keyed circuit turned on or off

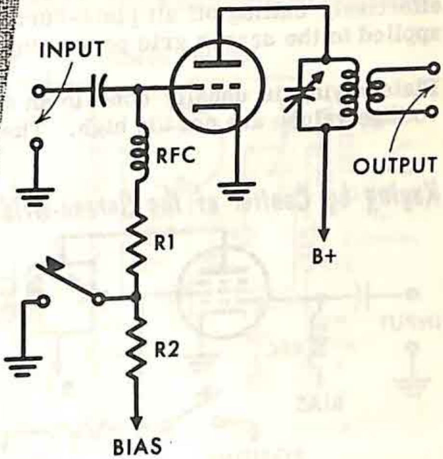


IMPROVED KEY-CLICK FILTER



KEYING BY CONTROL OF GRID EXCITATION

(Blocked-Grid Keying)



Another type of key click is caused by arcing at the contacts of the key. To remove these, a filter such as that shown is placed close to the key.

The question of which stage or stages to key in a transmitter is an important one. Keying the oscillator stage, or too close to it, can, as previously mentioned, cause chirping. If the oscillator circuit is stable, it can be keyed. However, any difficulty caused by keying the oscillator will be magnified by the succeeding amplifier and frequency-multiplier stages. Occasionally the problem of keying is eased by keying more than one stage, or using the previously mentioned keyer circuits. To enable clean keying of any stage there are various basic circuits. These circuits fall into two main categories: the first type controls the excitation, the second controls the voltage to the stage being keyed. A basic circuit for control of grid excitation is shown. With the key in the up position sufficient negative bias is applied to the grid of the tube to ensure its being cut off. With the key down, the bias voltage develops across R2 and is no longer applied to the grid of the tube. Resistor R1 acts to develop grid-leak bias.

Keying (Cont'd)

Keying by controlling voltages to the transmitter stage can be accomplished by as many means as there are tube electrodes. In a typical pentode with the suppressor grid internally connected to the cathode, keying can be accomplished at the cathode, screen grid, or plate. Cathode keying has been previously mentioned. Screen-grid keying can be accomplished to a degree by merely keying the screen-grid voltage from its normal value to zero. With zero screen voltage, however, there is still ample plate current flowing, providing backwave. To eliminate this backwave it is necessary to not only remove the positive screen voltage, but also to apply a negative screen-grid voltage to halt all plate current flow. A basic screen-grid keying circuit is shown. With the key up, a negative voltage is applied to the screen grid, effectively cutting off all plate-current flow. With the key down, a voltage is applied to the screen grid permitting normal operation of the stage.

Plate keying is usually done in an early stage of the transmitter where plate voltage values are not too high. The keying can take place in either the positive line of the circuit or in the negative line as shown. Most often it is done in the negative line since this permits one side of the key to be at ground potential.

Keying by Control of the Screen-Grid Voltage

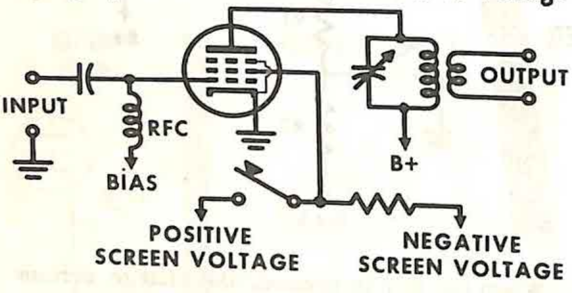
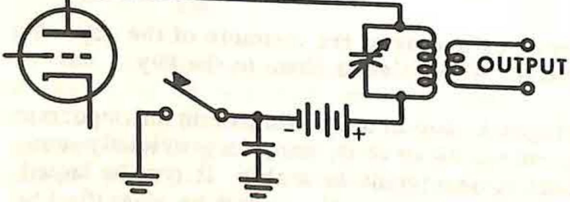
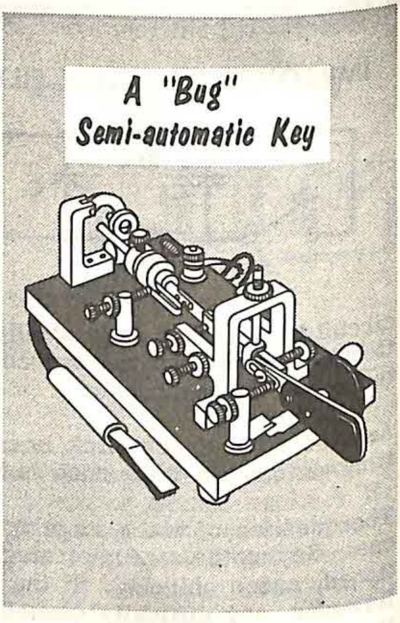


Plate Keying



A "Bug" Semi-automatic Key

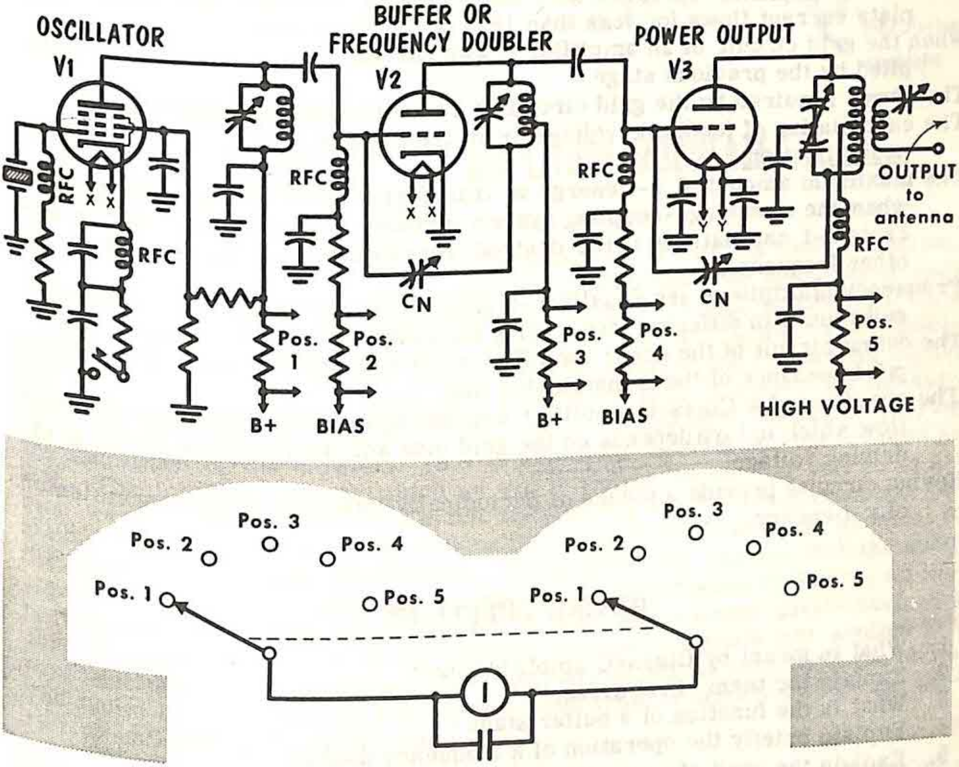


In addition to the usual hand-operated telegraph key there are semi-automatic telegraph keys, one of which is shown. Popularly known as a bug, the semi-automatic key will make continuous dots when the paddle is pressed to the right. These dots are made by a spring action that causes the contacts to open and close at a rate set by an adjustable weight.

Basic CW Transmitter

A typical basic low-power transmitter such as might be found in some ship-to-shore installation is shown. The oscillator being crystal-controlled is quite stable, and is therefore the stage that is keyed. The components in the cathode circuit of the oscillator form a key-click filter. The screen-grid voltage of V1 is developed by taking the B-plus applied to the plate and applying it to a voltage divider. The output of the crystal oscillator is capacitor-coupled to the grid of V2 which can be used as either a buffer or frequency doubler. Being a triode, when operated as a buffer with the output frequency the same as the input frequency, neutralization is necessary. The power-output stage is also neutralized.

BASIC CW TRANSMITTER



Metering is accomplished with a single meter switched in to read oscillator-plate and screen-grid current, buffer-grid current, buffer-plate current, the final grid current and the final plate current. The oscillator screen-grid current being small in value, usually about 2 or 3 ma, it does not interfere with the reading of a plate-current dip in the oscillator plate-tank circuit.

SUMMARY

Class-C amplifiers are used to amplify the output of the oscillator because of their efficiency. If triode tubes are used, they must be neutralized to prevent undesirable self-oscillation.

Buffers are used to prevent a power stage from loading down the stages preceding it. For example, a buffer is inserted between an oscillator and a power amplifier to prevent the power stage from changing the operating frequency of the oscillator.

A frequency multiplier is used to raise the output frequency of a crystal oscillator. It operates at some multiple of the oscillator frequency. It can be a frequency doubler, tripler, or quadrupler.

Power amplifiers are used in the output stages of transmitters to strengthen the modulated carrier for transmission. Usually, they are operated Class-C. Class-B can also be used in single-ended operation.

A Class-C amplifier operates with its grid-bias several times cutoff, thus plate current flows for less than 180° of the input cycle.

When the grid circuit of an amplifier draws current, the power must be supplied by the previous stage.

The power required by the grid circuit of a tube is called the grid drive.

The cancellation of feedback voltage from the plate to grid of a tube is called neutralization.

The maximum amount of r-f energy is transferred from one stage to another when the interstage-coupling system includes a tuned circuit which accepts r-f oscillations at the desired frequencies, and rejects r-f at all other frequencies.

Frequency multipliers are usually r-f amplifiers with input and output circuits tuned to different frequencies harmonically related to each other.

The output circuit of the power amplifier must be properly matched to the input impedance of the transmission line.

The operation of a Class-C amplifier depends upon the angle of plate-current flow which in turn depends on the grid bias and the amplitude of the grid-driving voltage.

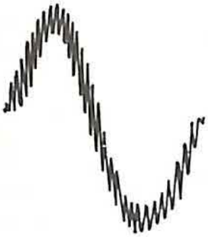
Keying circuits provide a means of periodically interrupting the transmission of r-f energy.

REVIEW QUESTIONS

1. What is meant by Class-C amplification?
2. Explain the term "grid drive."
3. What is the function of a buffer stage?
4. Explain briefly the operation of a frequency doubler.
5. Explain the need of neutralization.
6. What is the advantage of a push-pull power amplifier over a single-end type?
7. What is the function of a power-amplifier output-coupling network?
8. What are parasitic oscillations?
9. What is meant by keying?
10. Explain the operation of grid-bias keying.
11. What is link coupling?
12. What is cross neutralization?

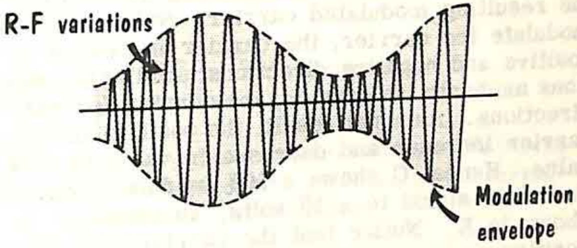
AM Transmission

RF and AF COMBINED IN LINEAR CIRCUIT



AUDIO WAVEFORM WITH R-F VARIATIONS

RF and AF COMBINED IN NONLINEAR CIRCUIT



AMPLITUDE-MODULATED R-F

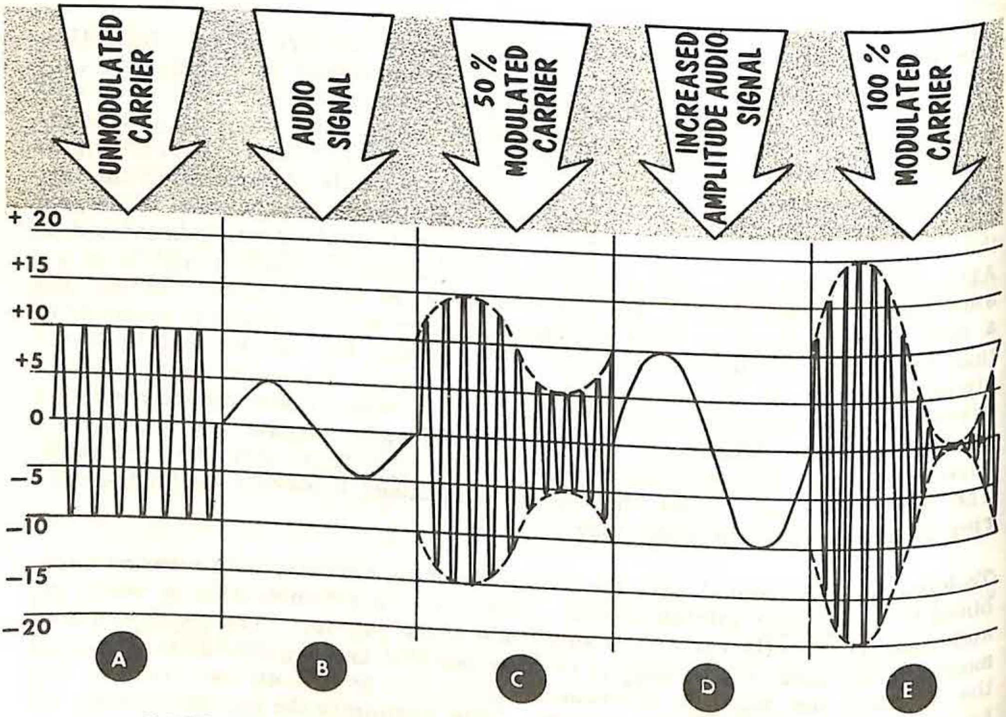
The word modulate as defined by a dictionary is "to vary in tone, inflection, pitch, or other quality of sound." In radio transmission we modulate or vary the r-f carrier. The unmodulated carrier is the r-f signal broadcast from a transmitter. It is called a carrier because it "carries" some form of intelligence. To have speech (or music) superimposed on the r-f carrier signal is to modulate the signal. There are several methods of modulating the carrier; the most popular, and the one we will discuss first, is that of varying the amplitude of the carrier. This is amplitude modulation, abbreviated as AM. The intelligence with which we will modulate the carrier will be an a-f sine wave. Actual speech and music frequencies are far more complex, but a sine wave permits a ready explanation of modulation which is identical to that caused by complex waveforms. To combine the carrier with the audio signal they are mixed together in special circuits discussed later. An important point is that the mixing can not be done with a linear device such as a pure resistance. When both the carrier and audio signals are applied to a pure resistance, they combine to have the carrier signal vary about the audio. The audio does not change the carrier amplitude; it merely swings the carrier up and down at the audio rate.

To have the audio signal vary the amplitude of the carrier, both must be combined in a nonlinear mixing circuit. The result is a combination in which the audio signal directly varies the amplitude of the carrier. The positive alternation of the audio signal adds to both the positive and negative alternations of the carrier; the negative alternation subtracts from both the positive and negative alternations of the carrier. This results in the carrier having two outlines of the audio signal. The upper outline is a duplicate of the original audio signal. The lower outline is also a duplicate, but 180° out of phase. Placing a dashed outline (called the envelope) on the modulated carrier shows up more clearly the outline of the audio signal.

AM Transmission (Cont'd)

The carrier amplitude is important; but more so, is the audio signal's amplitude compared to the carrier's amplitude. The amount or degree of modulation with which the audio modulates the carrier is rated in percent.

In A, we show an unmodulated carrier with a peak amplitude level of ± 10 volts. In B, we have a modulating audio signal of ± 5 volts peak. C shows the resulting modulated carrier. Notice that where the +5-volt alternations modulate the carrier, the carrier increases in the same amount in both the positive and negative directions; similarly, where the -5-volt audio alternations modulate the carrier, the carrier decreases in the same amount in both directions. As a net result, the positive and negative peaks of the modulated carrier increase and decrease in value by 50%, or one-half of its normal value. Hence, C shows a 50% modulated-carrier signal. We now increase the audio signal to ± 10 volts, as shown in D. The modulated carrier is shown in E. Notice that the carrier's amplitude is doubled on the audio's positive peaks, and reduced to zero at the audio's negative peaks. Hence the modulated carrier increases and decreases in value by a full 100%. Therefore, the carrier is said to be 100% modulated.



MODULATION PERCENTAGE VARIES WITH STRENGTH OF AUDIO SIGNAL

Percentage of Modulation

The degree of modulation in an AM wave is expressed by the percentage of maximum deviation from the normal amplitude of the r-f carrier. The effect of such a modulated wave, as measured by receiver response, is proportional to the degree, or percentage, of modulation.

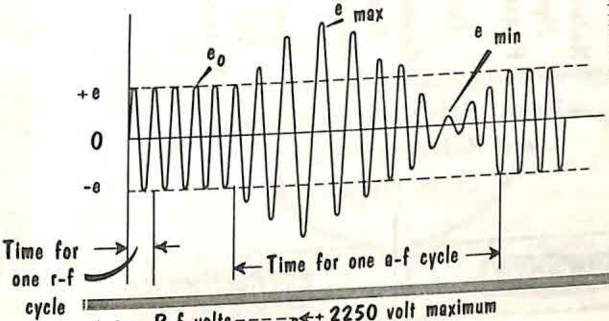
The percentage of modulation may be determined by the equation:

$$\text{Percentage of modulation} = \frac{e_{max} - e_{min}}{2e_0} \times 100$$

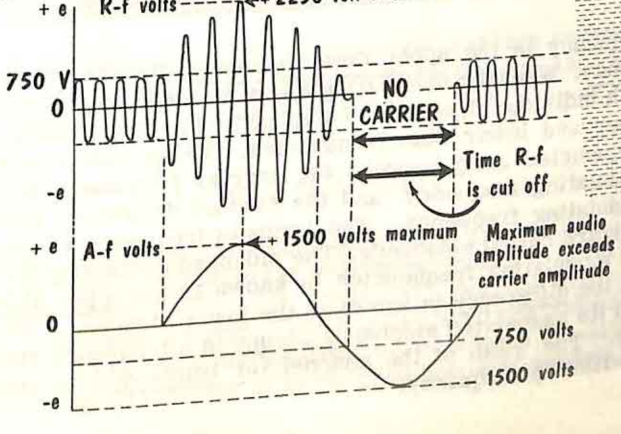
where e_{max} is the maximum instantaneous value of the r-f voltage, e_{min} the minimum instantaneous value of the r-f voltage, and e_0 the maximum instantaneous value of the r-f voltage in the absence of modulation.

It is important that the amplitude be varied as much as possible, because the output of a detector in a radio receiver varies with the amplitude variations of the received signal. Thus a comparatively low-powered, but well-modulated, transmitter often produces a stronger signal at a given point than does a much higher-powered, but poorly modulated, transmitter located the same distance from the receiver. If modulation exceeds 100% there is an interval during the audio cycle when the carrier is removed completely from the air.

ANALYSIS of MODULATED WAVE

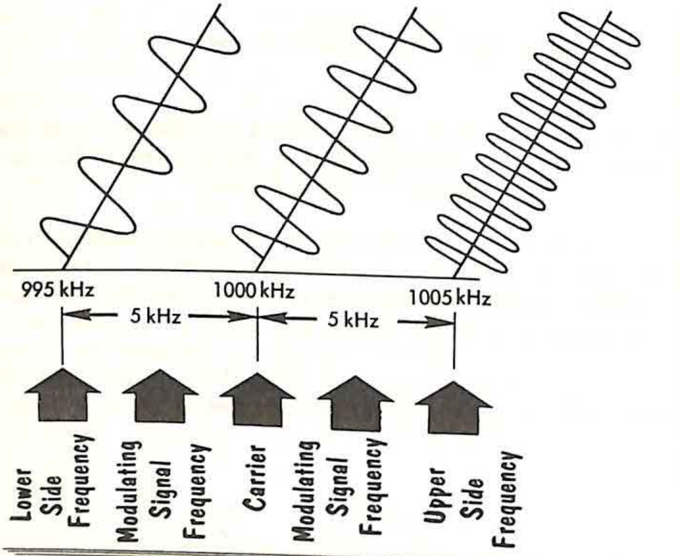


AMPLITUDE MODULATION in EXCESS of 100%

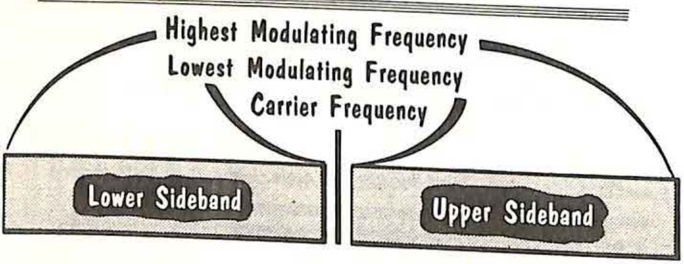


Sidebands

When an r-f carrier is modulated by a single audio note, two additional frequencies are produced. One is the upper frequency, which equals the sum of the frequency of the r-f carrier and the frequency of the audio note. The other frequency is the lower one, which equals the difference between the frequency of the r-f carrier and the audio note. The one higher than the carrier frequency is the upper side frequency; the one lower is the lower side frequency. When the modulating signal is made up of complex tones, as in music, each individual frequency component of the modulating signal produces its own upper and lower side frequencies. These side frequencies occupy a band of frequencies lying between the carrier frequency, plus and minus the lowest modulating frequency, and the carrier frequency plus and minus the highest modulating frequency. The bands of frequencies containing the side frequencies are called sidebands. The sideband containing the sum of the carrier and the modulating frequencies is known as the upper sideband; the band containing the difference is known as the lower sideband. The space which a carrier and its associated sidebands occupy in a frequency spectrum is called a channel. The width of the channel (or bandwidth) is equal to twice the highest modulating frequency.

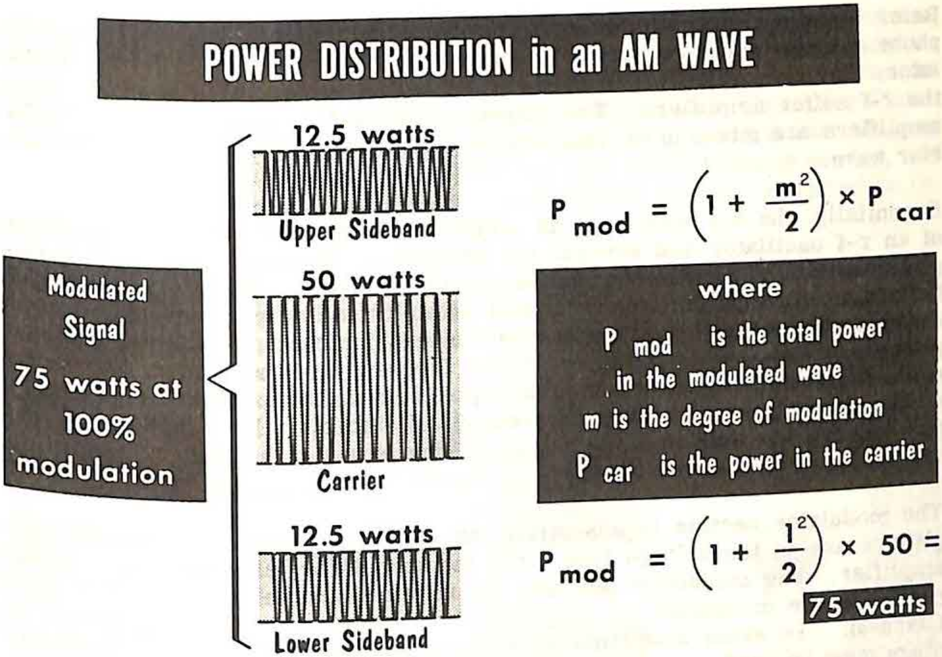


SIGNALS PRODUCED by MODULATING a 1000-kHz SIGNAL with a 5-kHz SIGNAL



SIDEBANDS PRODUCED by AMPLITUDE MODULATION

Power Distribution in an AM Wave


POWER DISTRIBUTION in an AM WAVE
Modulated Signal
75 watts at 100% modulation
12.5 watts
Upper Sideband
50 watts
Carrier
12.5 watts
Lower Sideband
$P_{mod} = \left(1 + \frac{m^2}{2}\right) \times P_{car}$
where
P_{mod} is the total power in the modulated wave
m is the degree of modulation
P_{car} is the power in the carrier
$P_{mod} = \left(1 + \frac{1^2}{2}\right) \times 50 =$
75 watts

The power in an amplitude-modulated wave is divided between the carrier and the sidebands. The carrier power is constant (except in cases of over-modulation), and so the sideband power is the difference between the carrier power and the total power in the modulated wave. When a carrier is modulated by a single sinusoidal tone, the total power output is found from the formula shown. Assuming that a 50-watt carrier is modulated 100%, the power in the signal is 75 watts. Of this total, 50 watts are in the carrier and 25 watts are in the sidebands. The percentage of sideband power, 25/75 times 100%, equals 33.3%. Of the 25 watts of sideband power, there are 12.5 watts in each sideband, and the power content of each is therefore 16.6% of the total power output with 100% modulation.

The available sideband power takes a marked drop when the average percentage of modulation is well below 100%. This is shown by modulating the carrier only 50%, when the power in the carrier is 50 watts.

$$P\ \text{mod} = \left[1 + \frac{(0.5)^2}{2}\right] \times 50 = 56.25 \text{ watts}$$

The total modulated power is now 56.25 watts. Since 50 watts exist in the carrier, only 6.25 watts of power remain in the sidebands. Since 6.25 watts are one-fourth the value obtainable with 100% modulation, we see that reducing the modulation to 50% causes a 75% reduction in the available sideband power. Since all the intelligence being transmitted is contained in the sidebands, the desirability of a high percentage of modulation becomes evident.

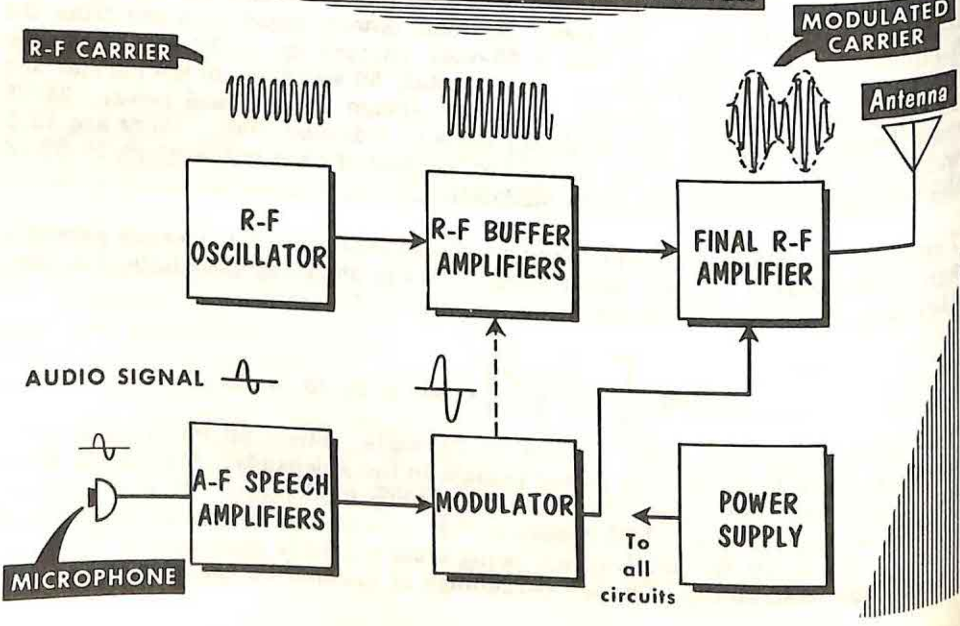
The Basic Amplitude-Modulated Transmitter

Referring to our diagram, we see that a feeble voice signal entering a microphone is amplified by several a-f speech amplifiers and also by the a-f modulator. The r-f oscillator produces the r-f carrier wave which is amplified by the r-f buffer amplifiers. The outputs of the a-f modulator and r-f buffer amplifiers are mixed in the final r-f amplifier to produce the modulated carrier wave.

Essentially, the r-f section of an amplitude-modulated transmitter consists of an r-f oscillator and several r-f amplifiers. In many cases, buffer amplifiers are used between the oscillator and the r-f amplifiers. As mentioned, buffer amplifiers isolate the oscillator from the following stages to minimize changes in oscillator frequency with changes in loading. Frequency multipliers are used to raise the oscillator frequency of the transmitter to the desired carrier frequency. It is desirable to have the oscillator operate at a comparatively low frequency for reasons of stability. Intermediate r-f amplifiers may be used to increase the driving power of the final r-f amplifier. The stage that the modulator feeds is known as the modulated r-f amplifier.

The modulator section is essentially an audio amplifier. The speech amplifiers are of the voltage type, with the modulator being basically a power amplifier. The modulator delivers the required amount of undistorted audio power to the modulated r-f amplifier. It may be operated Class-AB, or Class-B. To avoid distortion under these classes of operation, a push-pull stage must be used.

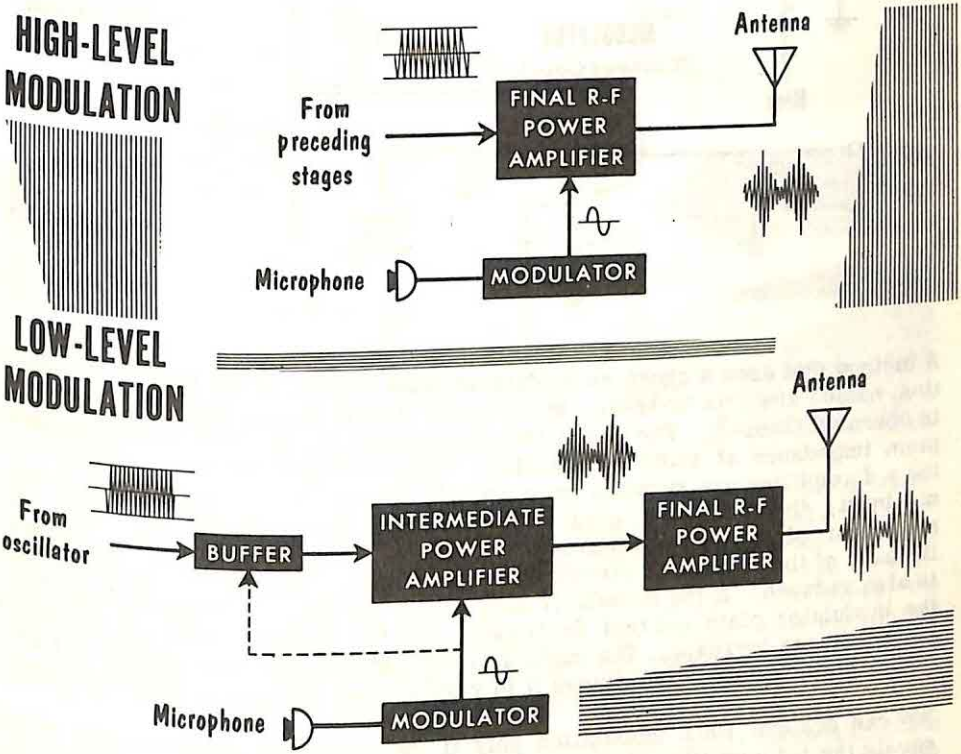
BLOCK DIAGRAM OF AM TRANSMITTER



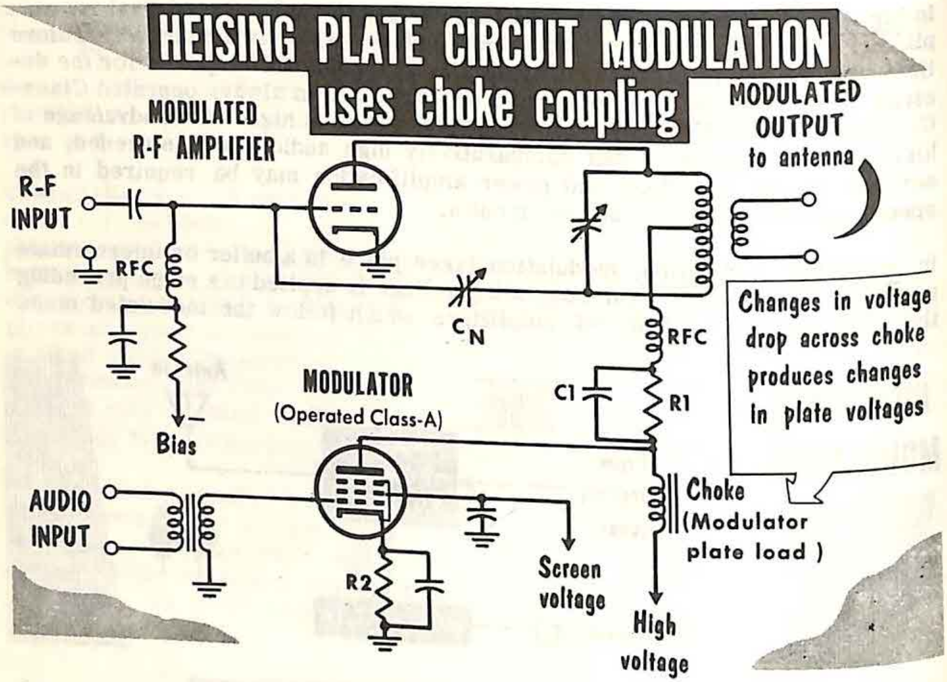
Modulation Levels

In high-level modulation the modulating voltage is applied to the final r-f amplifier. The stages preceding it need not be perfectly linear. Therefore they may be operated Class-C with operating potentials adjusted for the desired circuit efficiency and gain. The final stage is always operated Class-C. The overall efficiency of such a transmitter is high. A disadvantage of high-level modulation is that comparatively high audio power is needed, and several stages of voltage and power amplification may be required in the speech amplifier and modulator circuits.

In low-level modulation, modulation takes place in a buffer or intermediate power-amplifier stage, and modulating voltage is applied to a stage preceding the final amplifier. The r-f amplifiers which follow the modulated stage must be operated so that their a-c output voltages are amplified, undistorted replicas of the modulated r-f voltages applied to their grids. Since little a-f power is required to modulate the carrier fully, the a-f section of the transmitter can be made comparatively simple. A disadvantage of this system of modulation is that the modulated stage must be followed by linear r-f amplifiers. Since lower efficiency is usually obtained from linear amplifiers, efficiency of a low-level modulated transmitter is low as compared with that of a high-level modulated transmitter using the same type of tubes and identical d-c operating voltages.



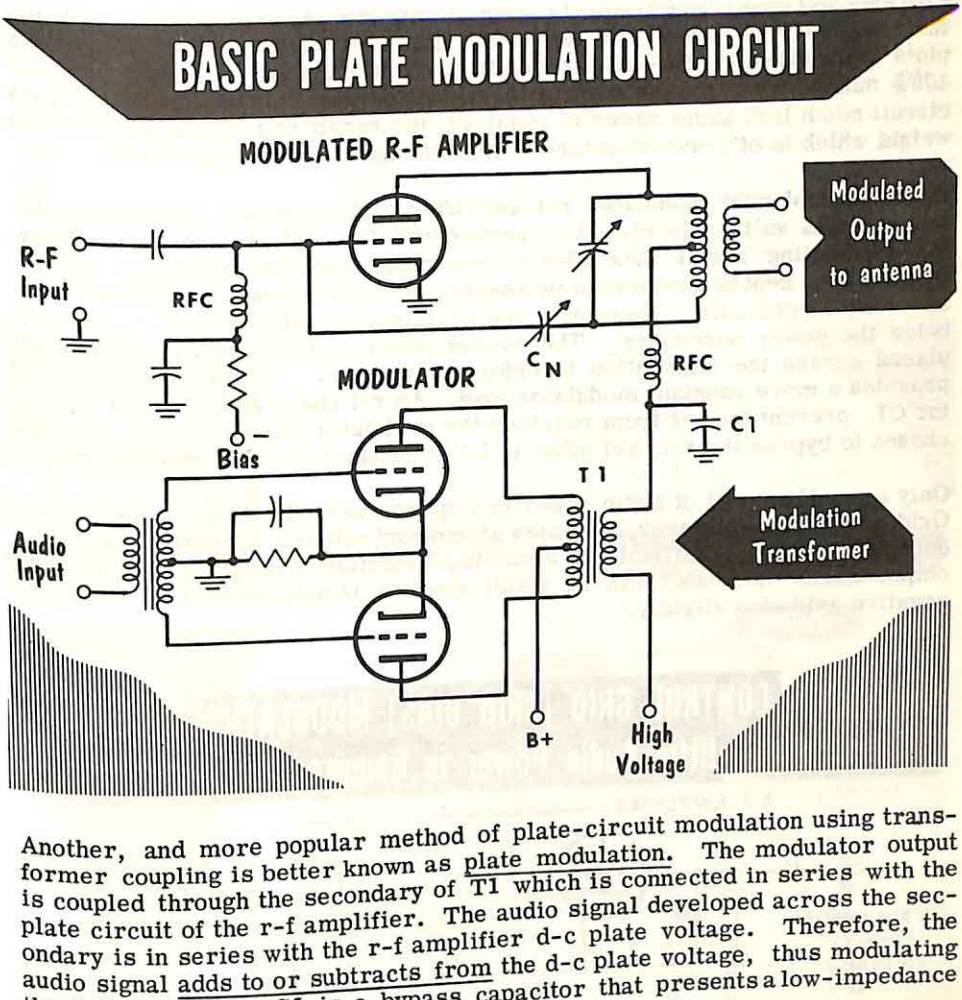
Heising Modulation


HEISING PLATE CIRCUIT MODULATION
uses choke coupling
MODULATED R-F AMPLIFIER
MODULATED OUTPUT to antenna
R-F INPUT
RFC
Bias
C_N
RFC
C1
R1
MODULATOR (Operated Class-A)
Changes in voltage drop across choke produces changes in plate voltages
AUDIO INPUT
Choke (Modulator plate load)
R2
Screen voltage
High voltage

A method that uses a choke as modulator plate load is called Heising modulation, named after its inventor. In the basic circuit shown, the modulator tube is operated class-A. The choke used as modulator plate load provides maximum impedance at audio frequencies. Plate voltages for the modulator and the r-f amplifier are supplied from a single source. If, due to an applied signal input, the modulator grid voltage swings in a positive direction, the modulator plate current increases. Hence, the plate voltage decreases. Because of the manner of circuit connection, the r-f amplifier's plate voltage is also reduced. If the modulator grid voltage swings in a negative direction, the modulator plate current decreases, and the modulator and r-f amplifier plate voltages increase. The modulator input signal thus controls the r-f amplifier plate voltage, and causes it to vary in step with the modulating signal.

We can achieve 100% modulation only if the modulator plate-voltage swing equals the r-f amplifier plate voltage. Thus, with a positive-going modulating signal the r-f amplifier plate voltage is doubled; a negative-going plate voltage reduces the r-f amplifier plate voltage to zero. The modulator plate voltage must therefore swing to zero. Any attempt to approach this condition would result in a severely distorted signal. To overcome this difficulty, the modulator plate voltage is increased to a value half that of the r-f amplifier by placing R1 in series with the r-f amplifier plate. Bypass capacitor C1 prevents R1 from acting as a plate load. R2 protects the grid circuit from drawing excess plate current when the modulator input signal drives the modulator grid positive.

Transformer Coupling (Plate Modulation)



Another, and more popular method of plate-circuit modulation using transformer coupling is better known as plate modulation. The modulator output is coupled through the secondary of T1 which is connected in series with the plate circuit of the r-f amplifier. The audio signal developed across the secondary is in series with the r-f amplifier d-c plate voltage. Therefore, the audio signal adds to or subtracts from the d-c plate voltage, thus modulating the r-f amplifier. C1 is a bypass capacitor that presents a low-impedance path to ground for any r-f, and a high reactance to a-f.

T1 requires special design. The primary must match the modulator plate impedance. The secondary impedance must permit a voltage swing that can provide 100% modulation. The transformer action permits 100% modulation without a voltage-dropping resistor such as is used in Heising modulation. Transformer coupling also lends itself to the use of high-efficiency circuits of Class-AB and -B modulators. When a tetrode or a pentode is used as an r-f amplifier, the screen grid acts as the main attraction for the electron stream, the plate being merely the collector of electrons. Since modulation of the plate only would be ineffective, the screen grid and the plate circuit are modulated. The screen receives its d-c voltage through R1, but the same modulated voltage is applied to the plate as well as to the screen.

Control-Grid Modulation

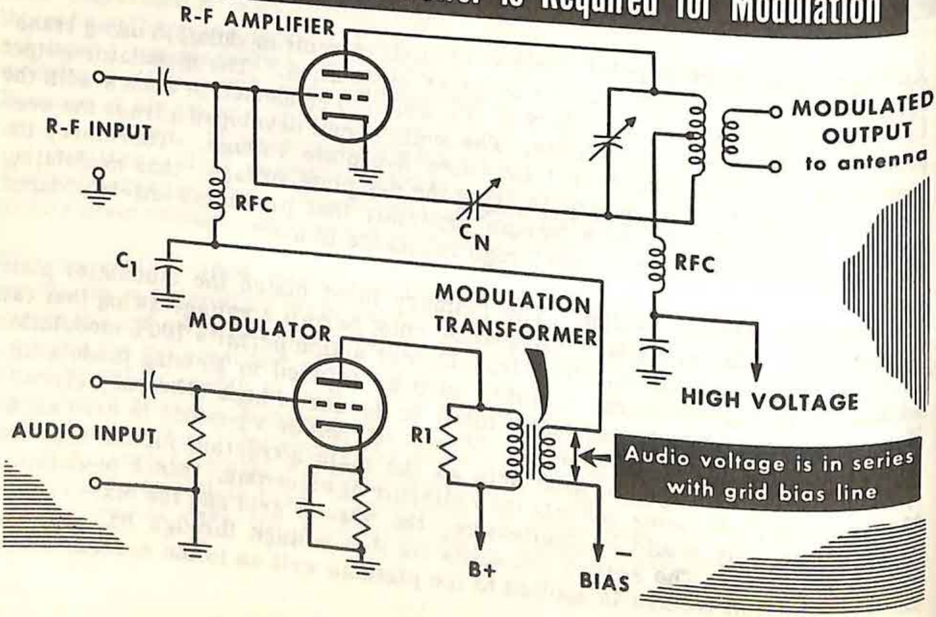
Economy and space requirements often dictate the use of modulating systems that require less power than is used in plate modulation. For example, in plate modulation, a 200-watt transmitter requires a 100-watt modulator for 100% modulation. By modulating the r-f amplifier through the control grid circuit much less audio power is required; the result is a saving in space and weight which is of great advantage in aircraft and mobile applications.

In the control-grid modulated r-f amplifier circuit shown, the audio modulating signal voltage is placed in series with the control-grid bias voltage. The modulating signal thus adds or subtracts from the grid-bias voltage. Distortion is kept to a minimum by keeping the load imposed on the modulator as steady as possible. Therefore, the modulator is often designed to provide twice the power necessary. The excess power is dissipated in resistor R1, placed across the modulation transformer primary. At the same time, R1 provides a more constant modulator load. An r-f choke and a bypass capacitor C1, prevent the r-f from reaching the modulator circuit. C1 is carefully chosen to bypass the r-f, yet offer a high impedance to the modulating a-f.

Only a small amount of audio power is required to modulate the control grid. Grid modulation, however, operates at reduced efficiency, and reduced power output, and there is difficulty in obtaining distortion-free output. The power output of the modulator can be small since it is only necessary to vary the negative grid bias slightly.

CONTROL GRID (GRID BIAS) MODULATION

Comparatively little Audio Power is Required for Modulation

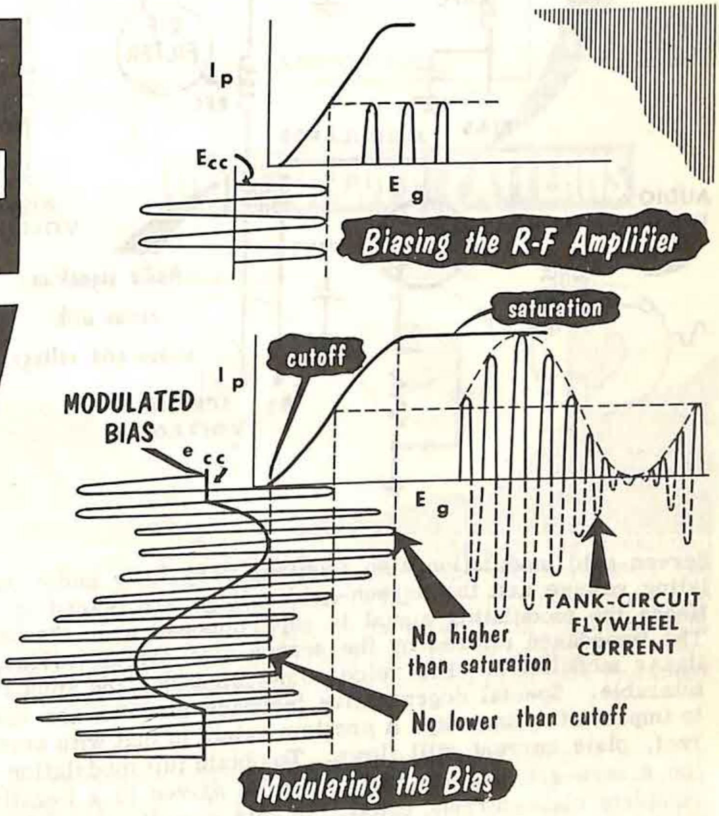


Audio voltage is in series with grid bias line

Control-Grid Modulation (Cont'd)

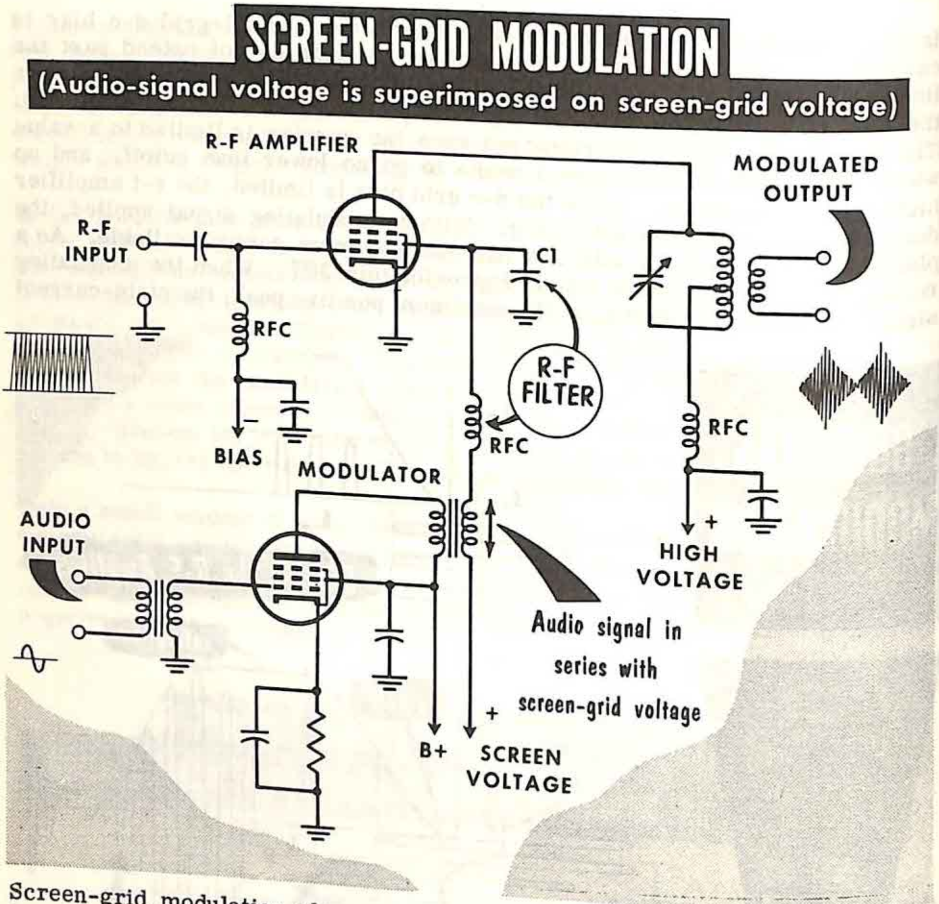
In the control-grid modulated r-f amplifier, the control-grid d-c bias is carefully adjusted so that the peaks of the carrier do not extend past the linear portion of the grid voltage – plate current curve, as shown. Unless the tube is operated on the linear portion of the curve, distortion results. The modulating signal superimposed upon the carrier is limited to a value which causes the carrier signal peaks to go no lower than cutoff, and no higher than saturation. Since the d-c grid bias is limited, the r-f amplifier does not operate at peak efficiency. With no modulating signal applied, the plate-current pulses are only one-half the maximum power available. As a result, the plate efficiency equals approximately 30%. When the modulating signal is applied, as shown, at the maximum positive peak, the plate-current pulses, for an instant, provide an efficiency of 75%. Hence, the plate efficiency of a grid-modulated stage varies from 30% (no modulation) to 75% (at 100% modulation). The increased efficiency provides the power in the sidebands. The required modulator power is very small; usually a voltage-amplifier stage is sufficient. Should the r-f amplifier draw a grid current, the power required of the modulator is still small. For example, a 1000-watt r-f amplifier can be modulated with 25 watts of audio power.

GRID-BIAS MODULATION


Biasing the R-F Amplifier

Modulating the Bias

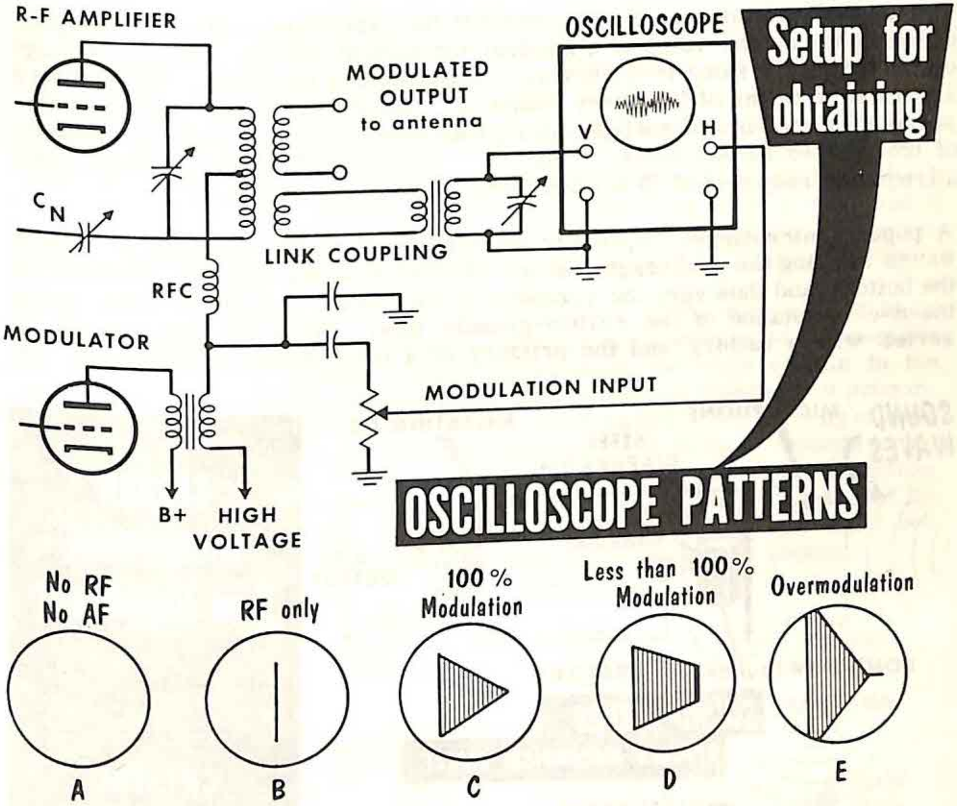
Screen-Grid Modulation



Screen-grid modulation also requires very little audio power. The modulating voltage and the screen-grid voltage are placed in series, as shown. Hence the modulating signal is superimposed upon the screen-grid voltage. The impedance offered by the screen-grid circuit varies, resulting in nonlinear modulation. For voice communication, the amount of nonlinearity is tolerable. Special degenerative feedback circuits are sometimes employed to improve the linearity. A problem exists in that with zero screen-grid current, plate current still flows. To obtain full modulation on negative peaks, the screen-grid voltage must often be driven to a negative value to obtain complete plate-current cutoff. In this circuit, the a-f power required for modulation is approximately one-fourth the power input to the screen under CW conditions. The peak audio voltage is approximately equal to the d-c screen voltage which is adjusted to one-half the value used for CW operation.

Screen-grid protection is obtained with a clamp tube which maintains a near-constant screen-grid voltage. The audio signal applied to the clamp tube modulates the screen-grid voltage.

Modulation Checking



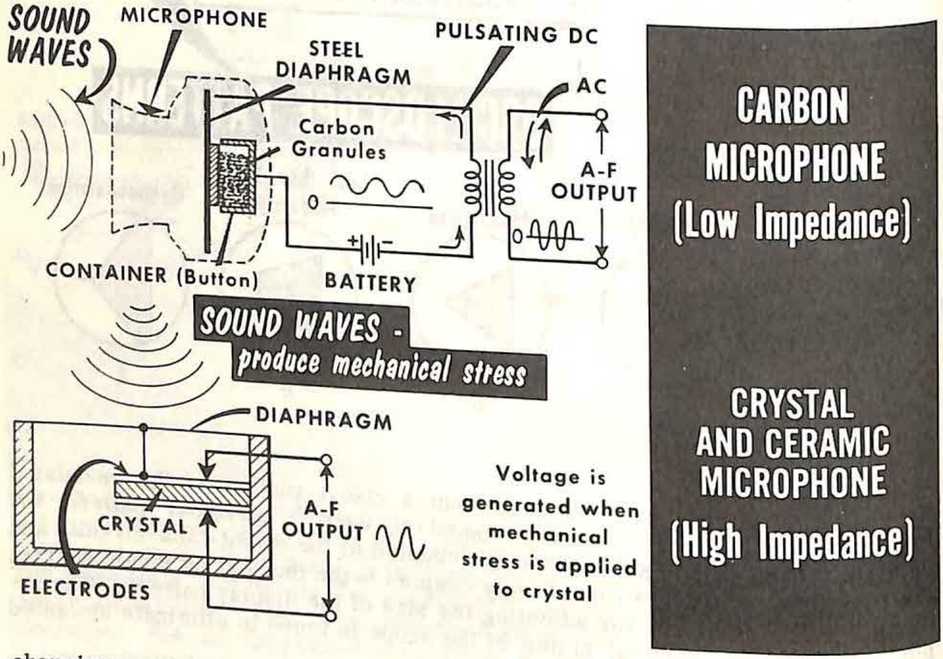
An oscilloscope can be used to present a visual picture of the modulated transmitter output. To obtain the popularly used "trapezoidal" pattern, the vertical plates of the oscilloscope are coupled to the output-tank circuit, and the horizontal plates are capacitively coupled to the modulating signal source, using a voltage divider, for adjusting the size of the display pattern. The input circuit to the vertical plates of the scope is tuned to eliminate unwanted harmonics.

In the absence of both excitation and modulation, the undeflected spot appears in the center of the screen (A). When excitation is applied, the spot swings upward and downward in step with the carrier-voltage variations, producing a vertical line on the scope screen (B). The length of the line represents the peak-to-peak amplitude of the carrier. When modulation is applied, the trapezoid pattern (C) is produced. This represents 100% modulation of a correctly adjusted transmitter. Diagrams (D) and (E) show a lower modulation percentage, and overmodulation, respectively. When the carrier is modulated 100%, the wide end of the pattern will be just twice the height of the carrier amplitude line of (B), while the narrow end will come to a point (C).

Microphones – Carbon and Crystal

The function of a microphone is to convert the variations in air pressure produced by the human voice or a musical instrument into an electrical voltage or current of the same frequency and corresponding amplitude. Microphones are rated in terms of frequency response, sensitivity, directivity, and impedance. A good broadcast-type microphone should have a frequency response of from 30 to 10,000 hertz, or higher. For general communications work, a frequency response of 75 to 4500 hertz would prove satisfactory.

A popular microphone, especially for mobile use, is the carbon type. Sound waves striking the diaphragm set up vibrations which vary the pressure on the button, and thus vary the pressure on the carbon granules. This varies the d-c resistance of the carbon-granule pile. Since the granules are in series with a battery and the primary of a microphone transformer, the changing resistance produces a corresponding change in the circuit current. The resulting pulsating dc in the primary produces an alternating voltage in the secondary. The transformer is used to step up the voltage as well as match the impedance of the low-impedance microphone with the high-impedance grid circuit. Microphone current may be from 10 to 100 ma, and the resistance may vary from 50 to 90 ohms.



CARBON MICROPHONE (Low Impedance)

CRYSTAL AND CERAMIC MICROPHONE (High Impedance)

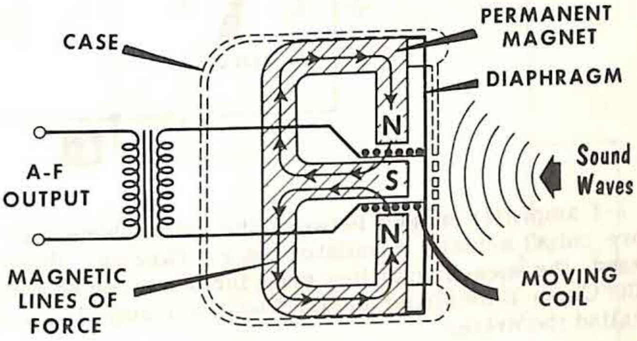
The crystal microphone uses a property of certain crystals such as Rochelle salts, known as the piezoelectric effect. The bending of the crystal, resulting from the pressure of the sound wave, produces an emf across the faces of the crystal. This emf is applied to the input of an amplifier. A man-made crystal (barium titanate) can also be used for a piezoelectric microphone. The barium titanate is produced in the form of a ceramic wafer similar to the crystal wafer, and is used in the same manner as the crystal

Microphones: Dynamic and Ribbon

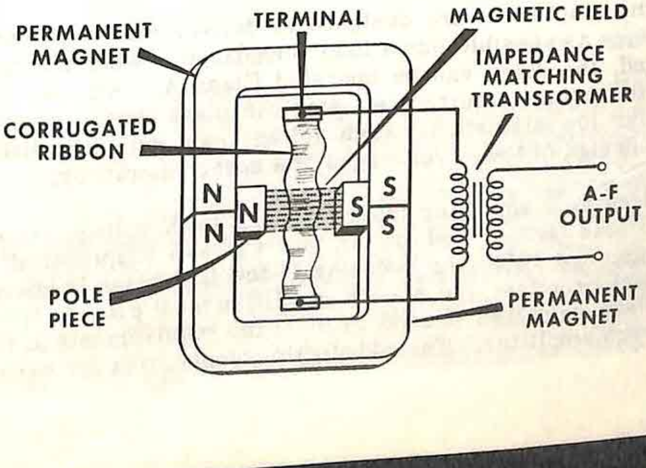
A dynamic or moving-coil type microphone consists basically of a coil of fine wire fastened rigidly to the back of a diaphragm so that it is suspended in the field of a strong permanent magnet. When sound waves make the diaphragm vibrate, the coil moves, cutting the magnetic lines of force of the magnet at the audio rate. This induces in the coil a voltage that is the electrical equivalent of the sound waves. The dynamic microphone is very sensitive, lightweight, and requires no external voltage. It is rugged, and has an excellent frequency response (a broadcast type may have a response of from 40 to 15,000 hertz); typical impedances are 50 to 500 ohms, thus requiring an impedance-matching transformer for connection to an amplifier.

The ribbon or velocity microphone is a variation of the dynamic. It has a thin, lightweight, flexible, corrugated, metallic strip suspended between the poles of a permanent magnet. Sound waves make the strip vibrate in the magnetic field. It cuts the lines of force, and voltage is induced in it proportional to the frequency and strength of the sound waves. The velocity microphone has good frequency response, but responds only to those sounds originating directly in front of it. Since the ribbon resistance is so low (less than 1 ohm) this microphone usually has a built-in transformer which raises its impedance to 250-500 ohms. The voltage output is very low, and leads between microphone and amplifier must be shielded to avoid hum pickup.

DYNAMIC MICROPHONE (Low Impedance)



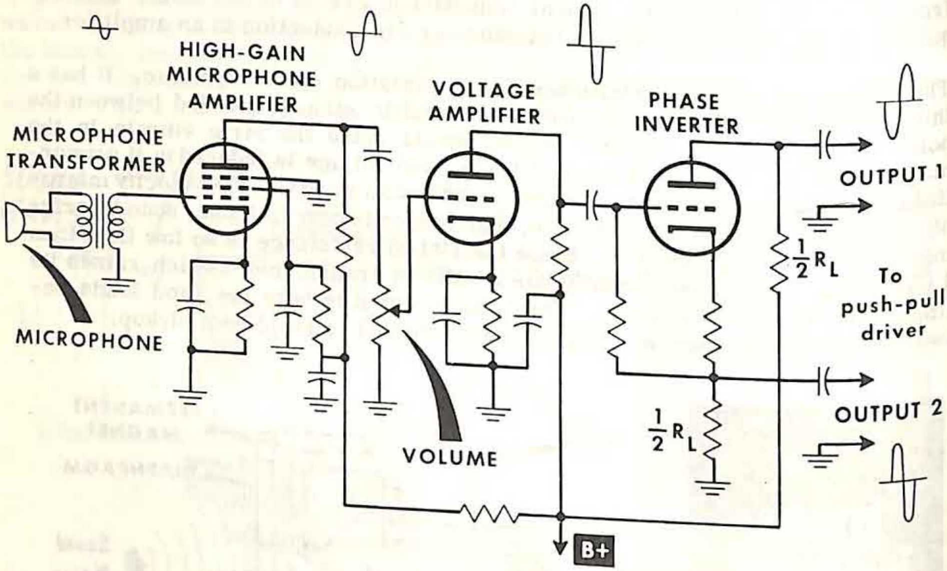
RIBBON MICROPHONE (Low Impedance)



Speech Amplifiers

The speech amplifier is used in a radiotelephone transmitter whenever the output of a microphone is lower than the signal voltage necessary to drive the modulator stage. Therefore, the speech amplifier is considered as all the a-f amplifier stages between the microphone and the input of the stage whose output actually modulates the r-f carrier. When a Class-B modulator is used, the speech amplifier must include a power amplifier to supply power to the Class-B amplifier grids. The power amplifier preceding the modulator is called the driver.

"Voltage Amplifier" Portion of Speech Amplifier

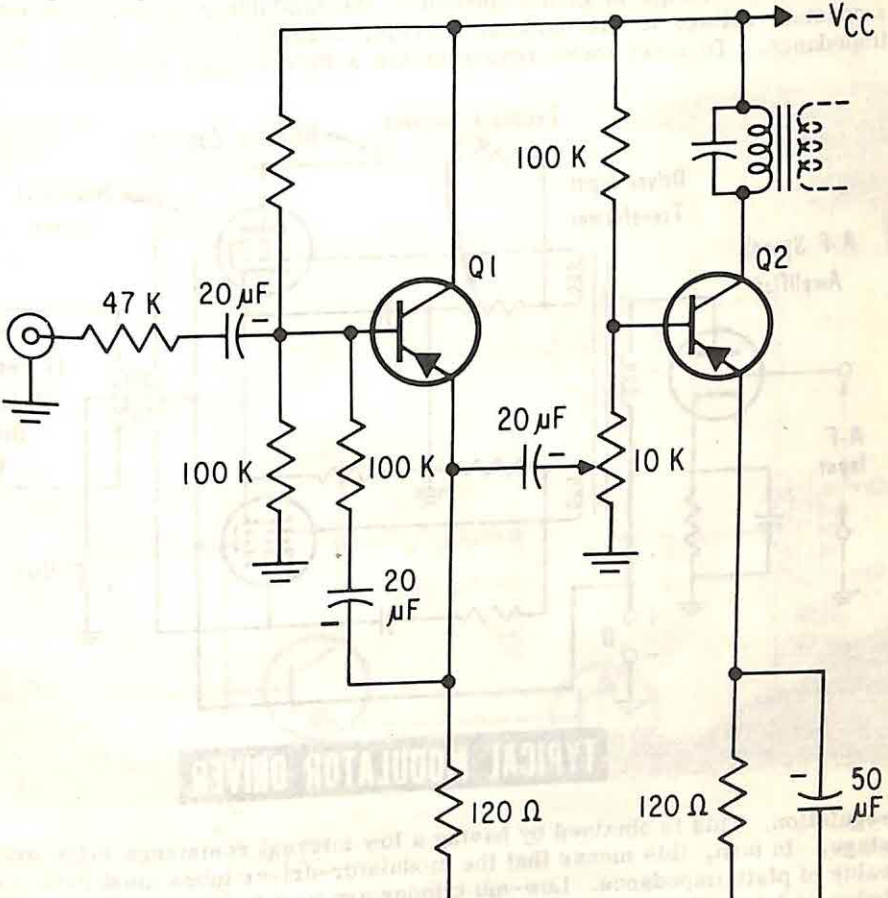


Audio amplifiers are designed to deliver either as much power or as much voltage as possible into a load impedance. When a large power output is desired, the stage can be operated Class-A, -AB, or -B. When voltage gain is the prime requirement, amplifiers are usually operated Class-A because of the low distortion. High voltage gain with low distortion is important in the design of low-level stages of a speech amplifier.

The speech amplifier must supply a peak voltage equal to the value of the d-c bias on the grid of the last Class-A amplifier if it is a single-ended stage, and twice the d-c bias if the last stage is operated in push-pull. In actual practice, the speech amplifier must provide from 25% to 100% more voltage gain than needed to meet the requirements at the grid of the last a-f speech amplifier. The added gain compensates for various circuit losses.

Speech Amplifiers (Cont'd)

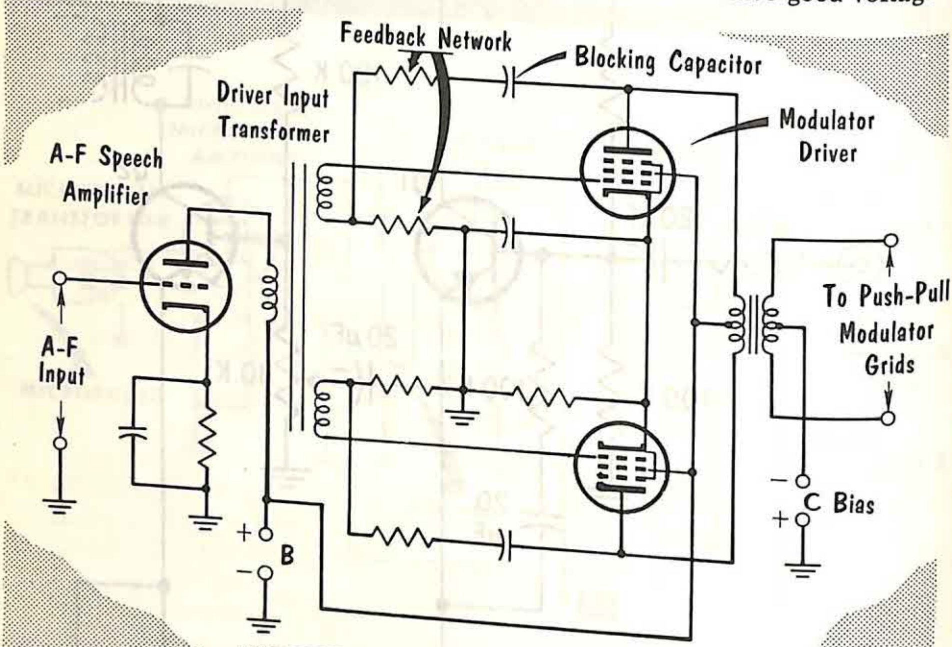
The transistor speech amplifier circuit uses Q1 as an emitter follower permitting use of a high-impedance microphone input, yet providing a low impedance output to Q2.



TRANSISTOR SPEECH AMPLIFIER CIRCUIT

Modulator Driver

The relationship between instantaneous grid voltage and grid current in Class-B modulators is not linear, and the grids present a varying impedance to the driver over the a-f cycle. To avoid distortion in the modulator caused by the change in grid impedance, the modulator driver must supply a constant voltage to the modulator grids, regardless of the change in grid impedance. To meet these requirements a driver must have good voltage regulation. This is obtained by having a low internal resistance in the driver stage. In turn, this means that the modulator-driver tubes must have a low value of plate impedance. Low-mu triodes are best for this condition. Pentodes and tetrodes can be used if sufficient inverse feedback is used to lower the effective plate impedance.

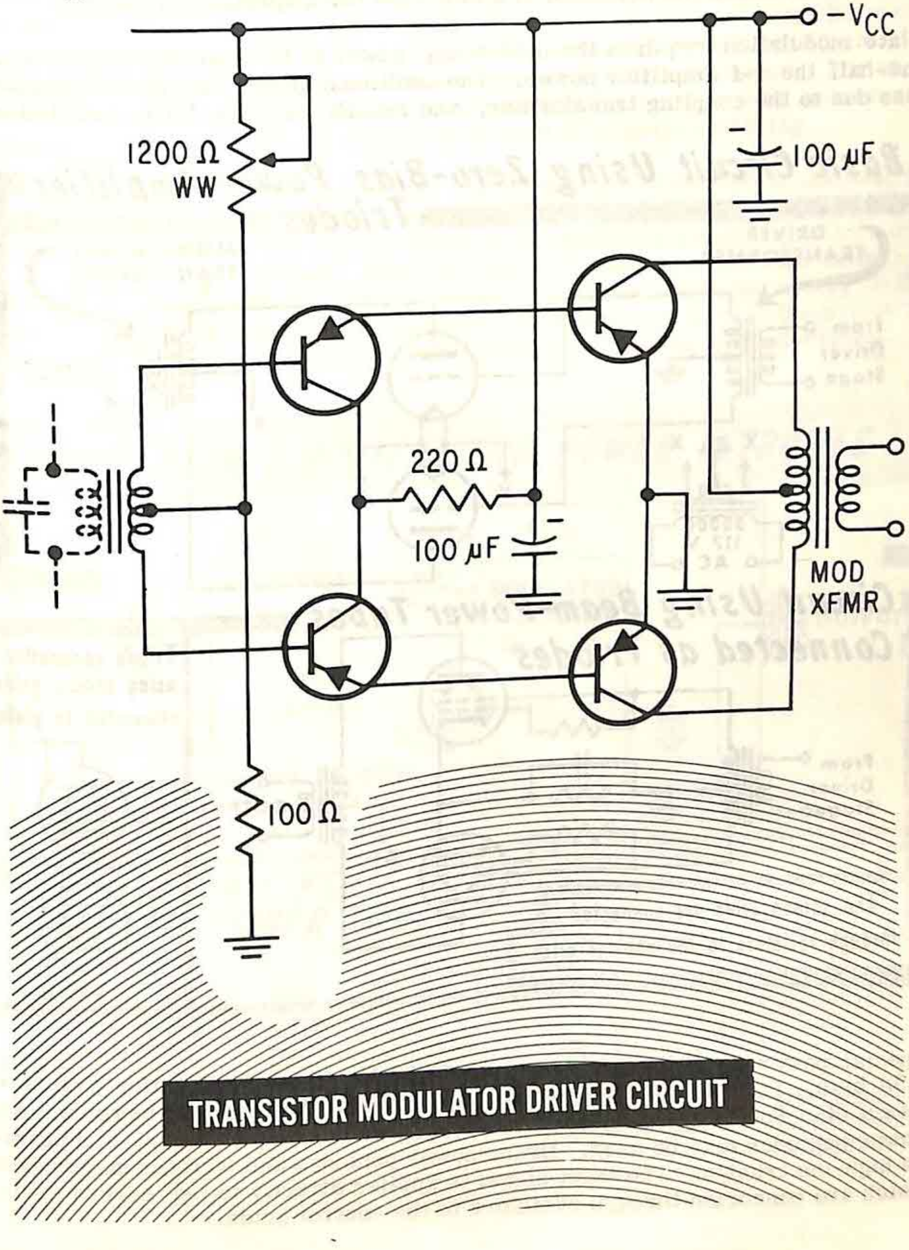


TYPICAL MODULATOR DRIVER

To obtain maximum power transfer from driver to modulator, we must match the higher driver plate impedance to the relatively low modulator input impedance. This is done by using a driver transformer having the highest possible voltage step-down between its primary and secondary. In this case, the plate resistance of the driver tubes, as seen by the modulator grids, is comparatively high. If high-mu triodes are used as Class-B modulators, they can be operated with very little or no d-c biasing voltage on their grids. This reduces the variation in grid impedance over the a-f cycle, and gives the driver a more constant input-impedance load. Distortion is thus reduced. Tubes operated in this way are often called zero bias tubes.

Modulator Driver (Cont'd)

The transistorized modulator driver continues from the transistorized speech amplifier shown on the preceding page. The use of direct coupling between the driver transistors and the power output transistors removes the need for an interstage audio transformer.

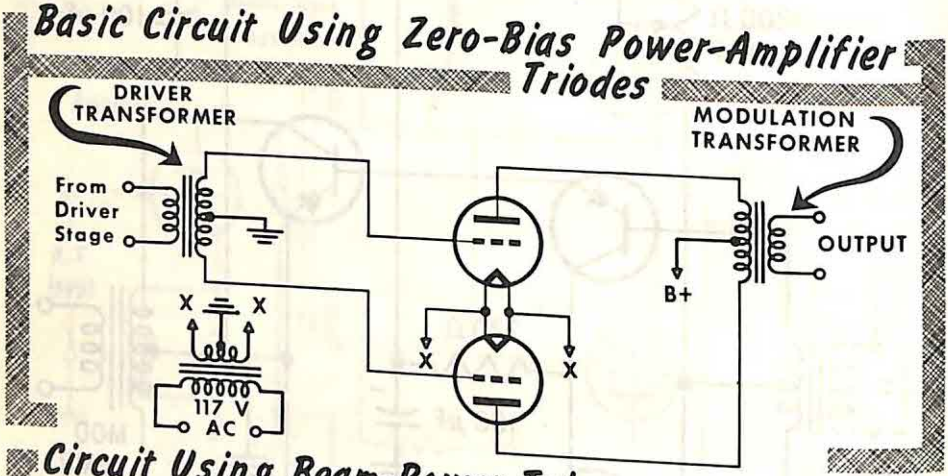


TRANSISTOR MODULATOR DRIVER CIRCUIT

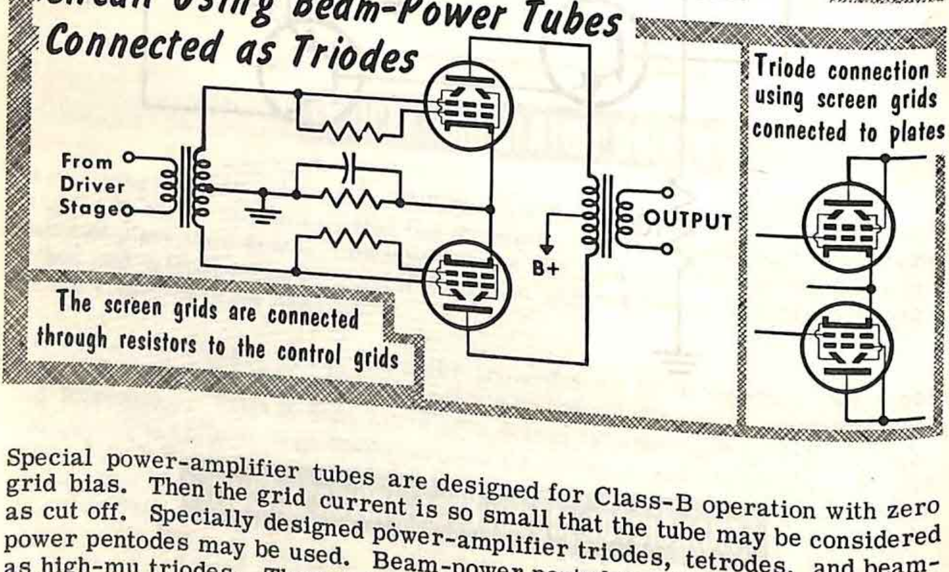
Modulator Stages

To obtain sufficient power from a modulator stage, Class-B operated push-pull amplifiers are most commonly used. Class-AB_1 and -AB_2 circuits are also found. The tubes in the modulator circuits are often of the same type as those used for r-f power-amplifier stages. The amount of audio power required determines the selection of a tube type for a specific application.

Plate modulation requires the modulating power to be somewhat higher than one-half the r-f amplifier power. The additional power covers any possible loss due to the coupling transformer, and readily permits 100% modulation.



Basic Circuit Using Zero-Bias Power-Amplifier Triodes



Circuit Using Beam-Power Tubes Connected as Triodes

From
Driver
Stage
OUTPUT
B+
Triode connection using screen grids connected to plates
The screen grids are connected through resistors to the control grids

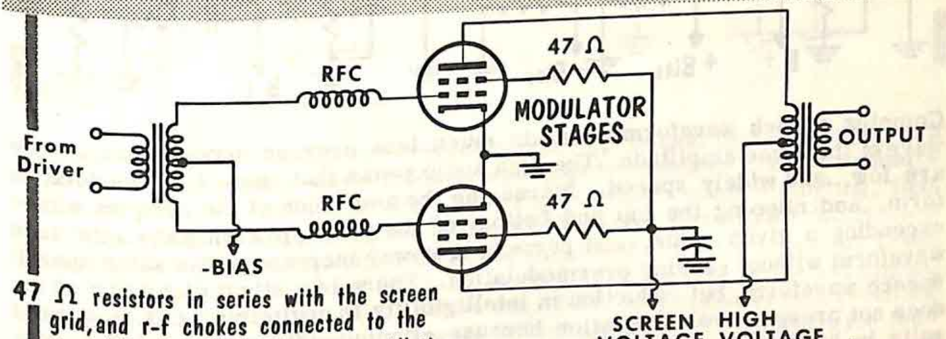
Special power-amplifier tubes are designed for Class-B operation with zero grid bias. Then the grid current is so small that the tube may be considered as cut off. Specially designed power-amplifier triodes, tetrodes, and beam-power pentodes may be used. Beam-power pentodes and tetrodes may be used as high-mu triodes. The input signal is applied directly to the screen grids, which are connected through resistors to the control grids.

Modulator Stages (Cont'd)

In the modulator circuit shown which uses a pair of power tetrodes, small resistors are connected in series with the screen grids; r-f chokes are connected to the control grids to avoid parasitic oscillations. In the low-power modulator circuit a voltage amplifier feeds a pair of beam-power pentodes. The modulation transformer is designed to match the plate-to-plate load impedance of the modulator tubes in the primary, and the load impedance of the r-f amplifier stage in the secondary. Commercial modulation transformers are available to match most of the popular tube combinations. For unusual tube combinations special transformers (universal) with numerous taps on both the primary and secondary permit impedance matching.

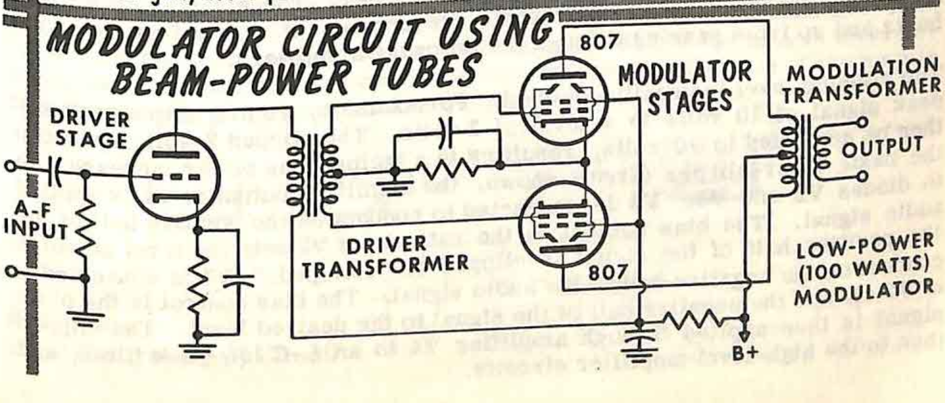
As an important special precaution, the modulation transformer secondary should always be under load. A dummy load of correct wattage and resistance is sufficient for the r-f amplifier to be operating and drawing the correct amount of plate current. When no load is connected across the modulation transformer secondary, the primary impedance rises to a very high value, and develops unusually large audio-signal voltages across the primary which may break down the transformer insulation, causing a short-circuit.

MODULATOR CIRCUIT USING POWER TETRODES



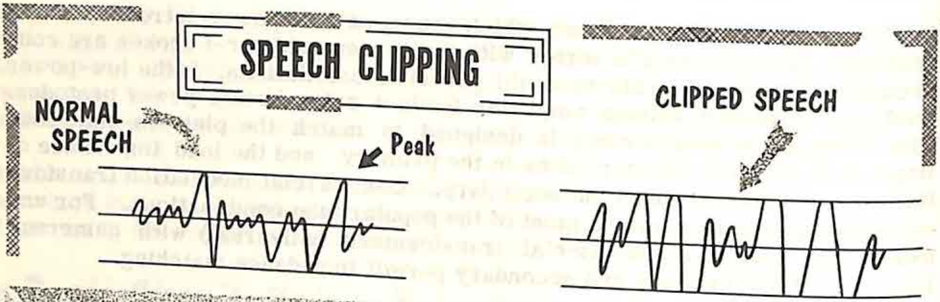
47 Ω resistors in series with the screen grid, and r-f chokes connected to the control grid, avoid parasitic oscillations

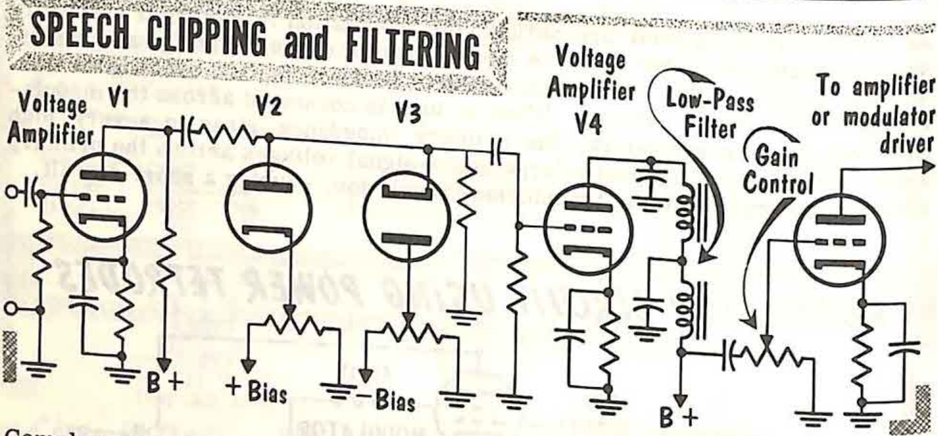
MODULATOR CIRCUIT USING BEAM-POWER TUBES



LOW-POWER (100 WATTS) MODULATOR

Speech Clipping and Limiting





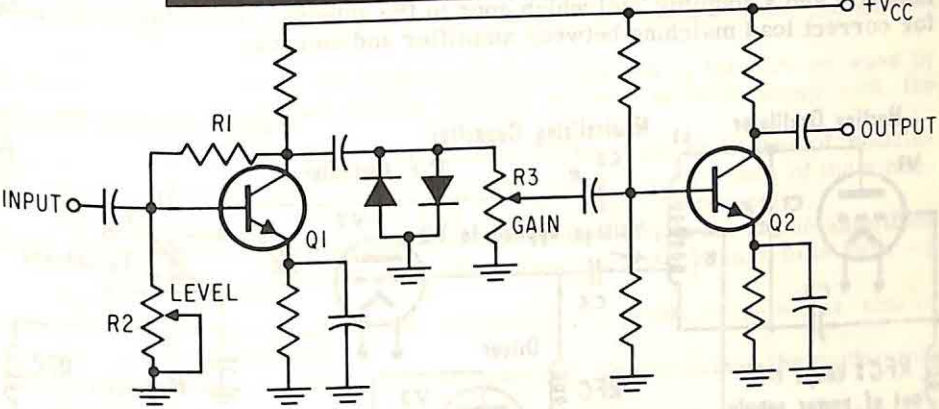
Complex speech waveforms contain much less average power than a sine wave of the same amplitude. The high audio peaks that cause 100% modulation are few, and widely spaced. Increasing the amplitude of the complex waveform, and clipping the top and bottom of the peaks, prevents the amplitude exceeding a given value, and permits a power increase of the same speech waveform without causing overmodulation. There is a slight distortion of the speech waveform, but reduction in intelligibility is negligible. Clipping itself does not prevent overmodulation because clipping, like overmodulation, results in high-frequency sidebands called splatter. Therefore, a filter follows the clipper circuit and prevents frequencies of approximately 3000 hertz and up from passing through the following amplifiers.

The clipping level is usually adjusted. For example, we may clip a peak-to-peak signal of 10 volts to a level of 2 volts. The clipped 2-volt signal can then be amplified to 10 volts, resulting in a tremendous power increase. In the basic filter-clipper circuit shown, the amplifier output of V1 is applied to diodes V2 and V3. V2 is connected to conduct on the positive half of the audio signal. The bias control in the cathode of V2 sets the level at which the positive half of the signal is clipped or "clamped." V3 is connected to conduct on the negative half of the audio signal. The bias control in the plate of V3 clamps the negative half of the signal to the desired level. The clipped signal is then applied through amplifier V4 to an L-C low-pass filter, and then to the high-level amplifier circuits.

Speech Clipping and Limiting (Cont'd)

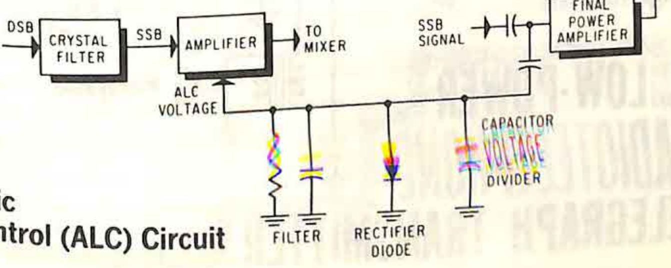
The transistorized speech clipper circuit shown utilizes two "back-to-back" diodes. The gain of Q1 is varied by R2 to set the clipping level. The combination bias voltage divider resistor and feedback resistor R1, reduces the gain of the input amplifier but provides helpful degeneration to reduce distortion. The back-to-back diodes limit the signal to approximately a 1/2 volt level which is then applied via the gain control to be amplified and applied as an output by Q2.

A TRANSISTOR SPEECH CLIPPER CIRCUIT



Automatic Limit Control (ALC)

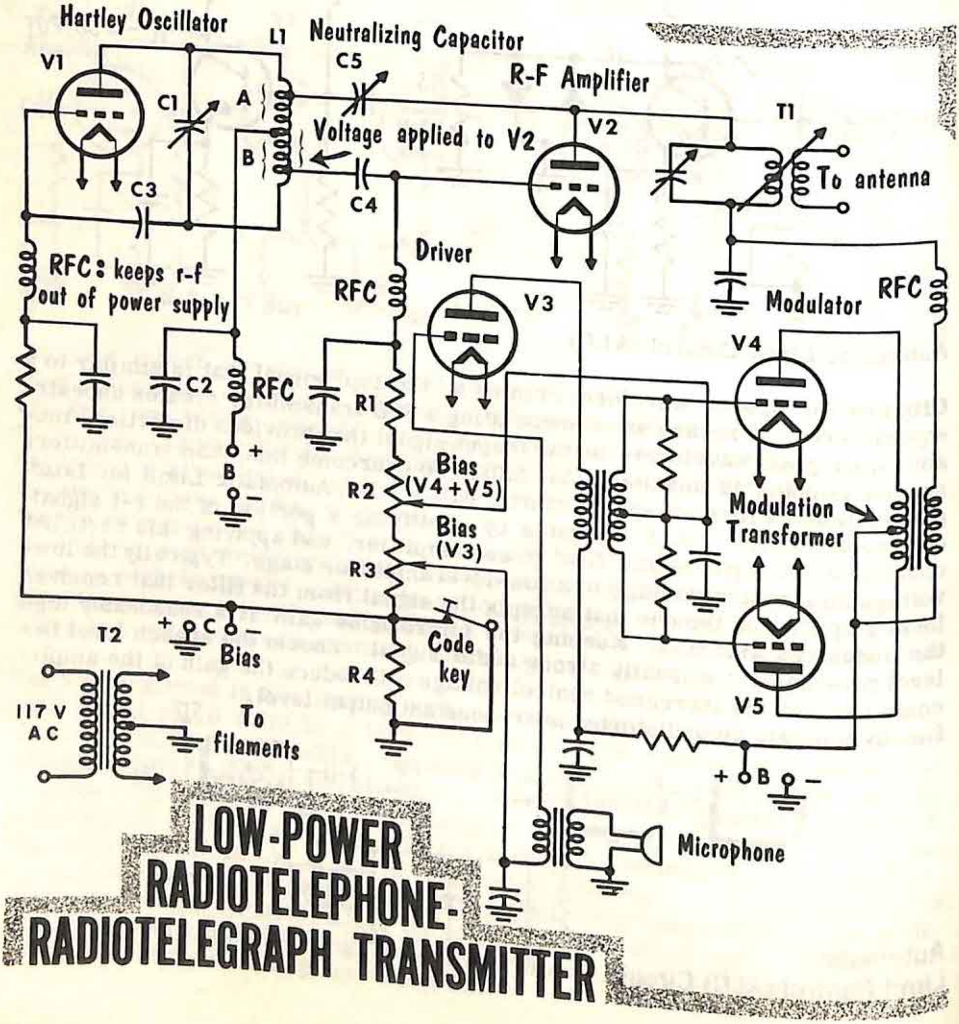
Clipping the speech waveform creates a "flat top" signal that is similar to a square wave. A square wave modulating a SSB transmitter creates undesirable high peak waveforms in the output signal that provides distortion, thus speech clipping is unsuitable for SSB. To overcome this, SSB transmitters generally use a form of speech control called ALC, Automatic Limit (or Load, or Level) Control. ALC operates by rectifying a portion of the r-f signal, usually at the input to the final power amplifier, and applying this rectified voltage as a control voltage to a low-level amplifier stage. Typically the low-level amplifier is the one that accepts the signal from the filter that removes the undesired sideband. Keeping the microphone gain at a reasonably high level provides a continually strong audio signal. Should the speech level become too high the increased control voltage will reduce the gain of the amplifier to maintain an undistorted near-constant output level.



Automatic Limit Control (ALC) Circuit

Basic CW-AM Transmitter

The transmitter shown uses a self-excited oscillator with L1-C1 making up the oscillator-tank circuit. Plate section A of L1 is between plate and filament, through C2, to ground and the centertap of T2; grid section B is between grid and filament, C3, C2, ground, and the centertap of T2. Coupling capacitor C4 is tapped on L1 to minimize oscillator loading. V2 bias is developed across R1-R2-R3 when key is closed. Oscillation in V2 is prevented by varying C5 to cancel out-of-phase voltages on grid. When the code key is open, negative voltage across R4 cuts off V2. V3 is the driver for class-B modulators V4 and V5. These stages are biased by the voltage developed by grid current flow in V2. R-f transformer T1 is the r-f modulated amplifier-tank coil and a coupling coil which goes to the antenna. Coupling is variable for correct load matching between amplifier and antenna.



LOW-POWER RADIOTELEPHONE-RADIOTELEGRAPH TRANSMITTER

Omega Drafting & Art Services

SUMMARY

Speech amplifiers are usually operated Class-A to keep distortion at a minimum. High voltage gain, low circuit noise, and low hum pickup are desirable.

Three principal types of microphones are used with speech amplifiers: the carbon, the crystal, and the magnetic. The carbon microphone has the highest output and the lowest fidelity; the magnetic has the lowest output and the highest fidelity.

The modulator builds up the audio signal and modulates the r-f carrier with its output. It is usually operated Class-B for relatively high power and fidelity.

If the audio-signal output of the modulator is injected into the final power amplifier, the process is called high-level modulation. If it is injected into some preceding stage, the process is called low-level modulation. The audio signal can be injected at any grid, or at the plate of the modulation stage.

In amplitude modulation, intelligence is superimposed on the carrier wave by causing the amplitude of the carrier to vary in accordance with the modulating signal.

The percentage of modulation is a measure of the depth or degree of modulation of a carrier wave. It is dependent upon the amplitude of the modulation envelope as compared with the amplitude of the carrier.

If the amplitude of the modulation envelope is twice as great as the amplitude of the carrier, then the modulated wave formed is said to be full, or 100% modulated.

When an r-f carrier is modulated, sidebands are produced on either side of the carrier frequency.

Sidebands are equal in frequency to the carrier, plus or minus the modulating frequency.

The power in an amplitude-modulating wave is divided between the carrier and the sidebands.

Plate modulation is most commonly used for high-level amplitude modulation.

In plate modulation the modulating voltage is impressed on the d-c supply voltage of one of the r-f amplifiers of the transmitter.

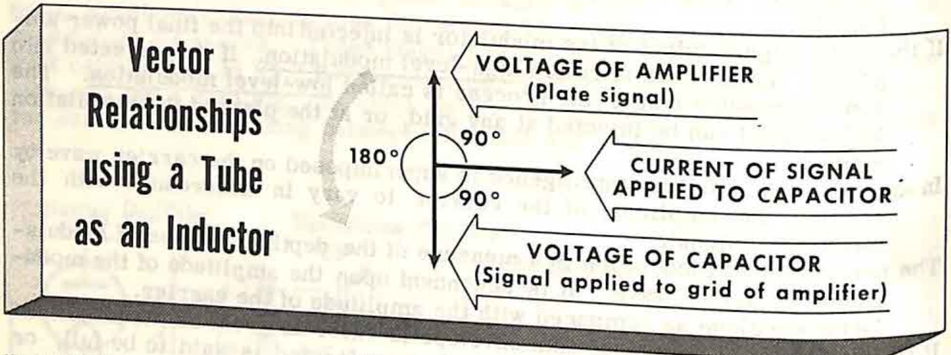
A speech amplifier is needed in a radiotelephone transmitter whenever the output of the microphone is lower than the signal voltage required to drive the modulator tube.

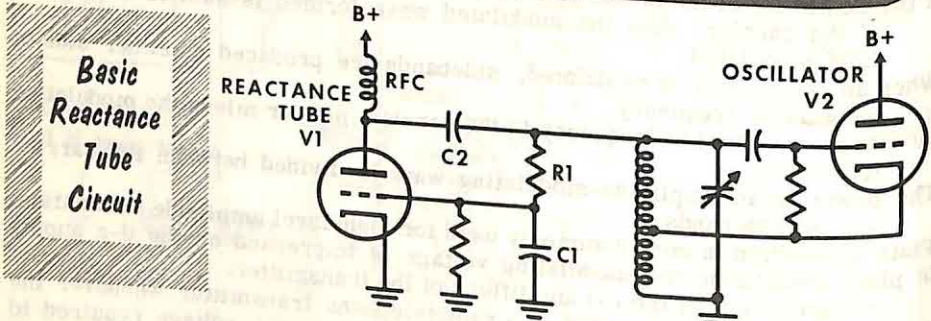
REVIEW QUESTIONS

1. What is meant by amplitude modulation?
2. What is meant by percentage of modulation?
3. What function do sidebands serve?
4. Explain Heising modulation.
5. What is meant by high-and low-level modulation?
6. Explain control-grid modulation.
7. Describe the operation of a carbon microphone.
8. Describe the operation of a dynamic microphone.
9. What circuits are included in the speech amplifier?
10. What is the function of the modulator drive stage?
11. What class of operation can be used in the modulator stage?
12. Describe a simple test procedure checking modulation.

Direct FM

The two most popular methods of developing an FM signal are by the direct and indirect methods. In the direct method an oscillator is modulated directly by the audio signal. In the indirect method, phase modulation is used to vary the carrier to create an FM signal. The simplest method of producing an FM signal is to have the modulating signal vary the value of L or C in an oscillator, causing the frequency to vary. This basic concept is illustrated by having a capacitor microphone placed directly across the tuning capacitor of a Hartley oscillator. The oscillator frequency is determined by the total L and C in the tank circuit. When sound waves strike the movable plate of the microphone, the capacitance will increase and decrease in accordance with the sound wave. More capacitance means a lower frequency; less capacitance means a higher frequency. The result is a frequency-modulated wave.


Vector Relationships using a Tube as an Inductor
VOLTAGE OF AMPLIFIER
(Plate signal)
90°
180°
90°
CURRENT OF SIGNAL APPLIED TO CAPACITOR
VOLTAGE OF CAPACITOR
(Signal applied to grid of amplifier)



A refined system for producing FM involves the use of a tube to vary the frequency of the tank circuit, rather than the microphone. We know that in a pure inductance E leads I by 90°; in a pure capacitance I leads E by 90°. A tube can act as an inductance by having plate voltage lead grid voltage by 90°; it can act as a capacitance by having plate voltage lag grid voltage by 90°. A reactance tube can be made to act as a capacitance or an inductance. How a tube can be made to act as an inductance is shown vectorially. A signal applied to a capacitor will have its voltage lag its current by 90°. The capacitor voltage is then applied to the amplifier, with the tube inverting the signal by 180°. Note that the plate signal leads the signal current by 90°.

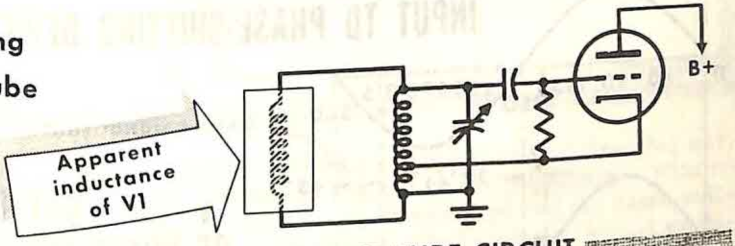
Direct FM (Cont'd)

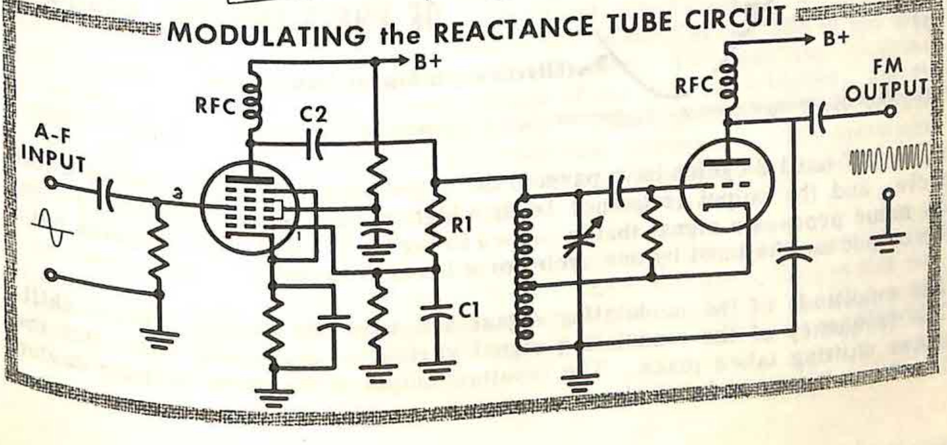
In the basic reactance-tube circuit the oscillator tank is paralleled by R1 and C1, placing the tank-signal voltage across these components. The resistance of R1 is much higher than the reactance of C1. Therefore, the R1-C1 circuit acts as a resistance, and the current flowing in it is in phase with the voltage of the tank circuit. The signal voltage across C1 lags the signal current by 90°. The tube amplifies the capacitor-signal voltage. This appears at the plate 180° out of phase with the grid voltage, and places the plate voltage 90° ahead of the signal current flowing through R1-C1. The plate-voltage signal is coupled back to the tank circuit by C2, a high-value low-reactance capacitor that couples the output signal and isolates the plate voltage from the tank circuit. The net result is to have V1 act as though it were an additional parallel inductance across the tank circuit inductance.

To put the reactance tube to work as a modulator, a pentagrid converter tube is used. The tank-circuit signal is applied to grid 1 with R1, C1, and C2, causing the tube to act as a reactance. The modulating audio signal is applied to grid 3 to modulate the reactance tube.

The variations in plate current caused by the audio signal determine to what degree the reactance tube will act as an inductor. These variations in turn cause the oscillator-tank circuit to change frequency accordingly. The frequency of the modulating signal results in the equivalent number of changes in the frequency of the oscillator. The amplitude of the modulating signal determines to what amount the reactance tube will vary, in turn determining to what extent the frequency of the oscillator will shift.

Result of Placing a Reactance Tube across the Tank Circuit

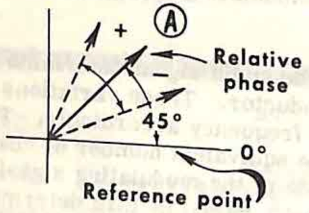



MODULATING the REACTANCE TUBE CIRCUIT

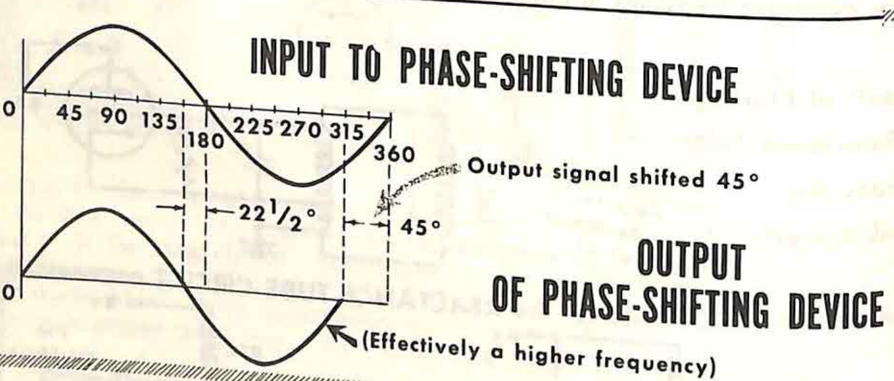
Indirect FM

The oscillator circuit used in the direct system of FM cannot be crystal controlled. This presents a problem in maintaining high-accuracy frequency control. The indirect method of FM permits the use of a crystal-controlled oscillator whose steady carrier output is phase modulated to produce FM.

To understand how phase modulation can create frequency modulation we will use a phase-shifting device set for 45° phase shift. A sine-wave input signal of constant frequency and amplitude is applied to the input terminals; the output terminals will have the same signal shifted to lead (or lag) by an amount determined by the phase-shifting device. As shown, the phase shifter is set to cause a 45° lead in the output signal. The output signal completes its cycle 45° ahead of the input signal. Each succeeding cycle will see the output leading by 45° until 8 cycles have passed; the output signal will then lead by a full cycle, and the output frequency is thus higher than the input frequency. By the same process a signal that is caused to lag by 45° will after 8 cycles have the output lag the input by one cycle for a lower frequency.



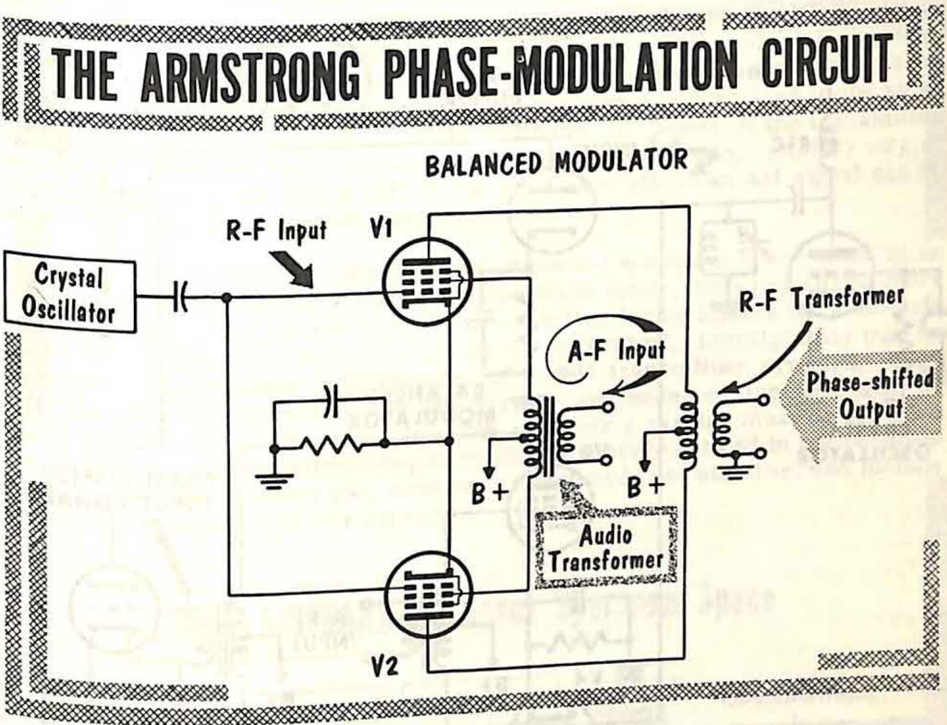
Ⓐ is the phase-modulated carrier of 45° relative phase, and is constant in length. Phase deviation results when the vector varies above and below its relative phase angle as indicated by the dotted vectors.


INPUT TO PHASE-SHIFTING DEVICE
0
45
90
135
180
225
270
315
360
Output signal shifted 45°
22½°
45°
0
OUTPUT OF PHASE-SHIFTING DEVICE
(Effectively a higher frequency)

The amplitude of the modulating signal will vary the degree of phase shift. The frequency of the modulating signal varies the frequency with which the phase shifting takes place. The resultant output of the phase-shifting device is a frequency-modulated signal.

The Armstrong Phase-Modulation Circuit

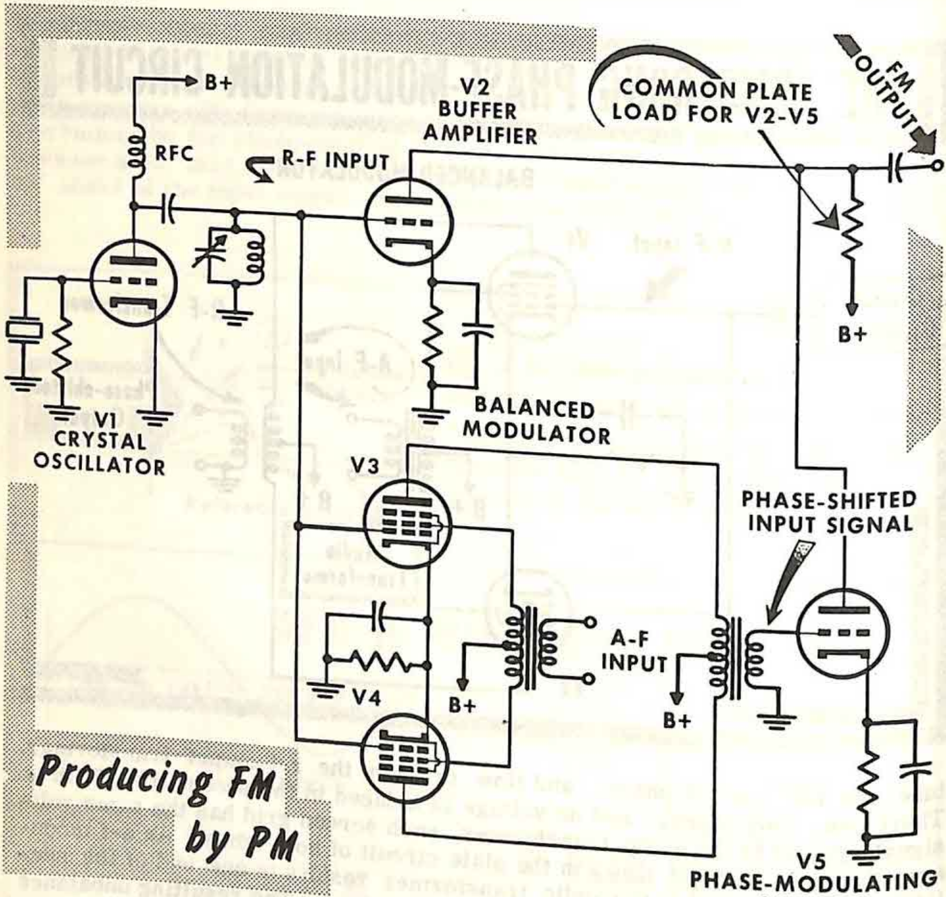
A circuit derived by Armstrong to achieve FM through PM uses the balanced-modulator stage. The circuit operates as follows: the output of a crystal oscillator is applied to the control grids of V1 and V2 in phase. The plate load for both tubes is a centertapped r-f transformer. The plate currents of each tube are 180° out of phase, and flow through the r-f output transformer. Therefore, they cancel, and no voltage is induced in the secondary. With no signal applied to the audio transformer, each screen grid has the same voltage; the same current flows in the plate circuit of both tubes. An a-f modulating signal applied to the audio transformer results in one end of the secondary being more, or less positive than the other. The resulting unbalance in the secondary causes the screen voltage of one tube to be higher, and the screen voltage of the other tube to be lower. Consequently the plate current of one tube increases, and that of the other tube decreases. The plate currents flowing in the r-f transformer primary are no longer equal but opposite in phase, and a voltage is now induced in the secondary.



The phase-shifting action of the tubes and the r-f transformer cause the r-f transformer output voltage to lead or lag the input voltage of the crystal oscillator. The phase shift leads or lags depending upon whether the plate current of V1 or V2 is increased. The amount of phase shift is determined by the modulating signal amplitude.

Phase Modulation (PM)

In the complete indirect FM circuit shown, the phase-shifted output of the r-f transformer secondary is applied to the amplifier tube V5. The crystal-oscillator output is applied to the balanced modulator and to the buffer amplifier V2. Tubes V2 and V5 use a common plate load. The phase-shifted output of V5 phase modulates the output of V2. The resultant phase-modulated output of both tubes is changing in frequency to provide an FM output.



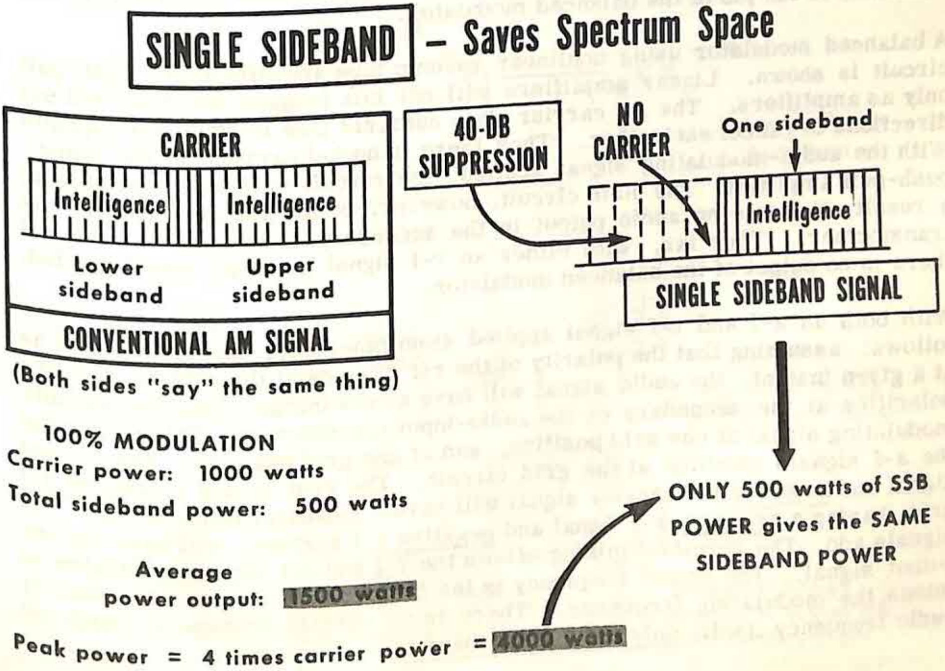
Producing FM by PM

The degree of frequency swing of either the direct or indirect FM systems must be carefully controlled because the following stages consist of frequency-multiplier circuits that multiply both the center (zero-signal) frequency and the frequency deviation. The transmitter circuits used for FM transmitters are closely identical with those of AM transmitters. Frequency-multiplier circuits must use broader tuned circuits that are not too selective since the bandwidth used in FM is wider than that used in AM.

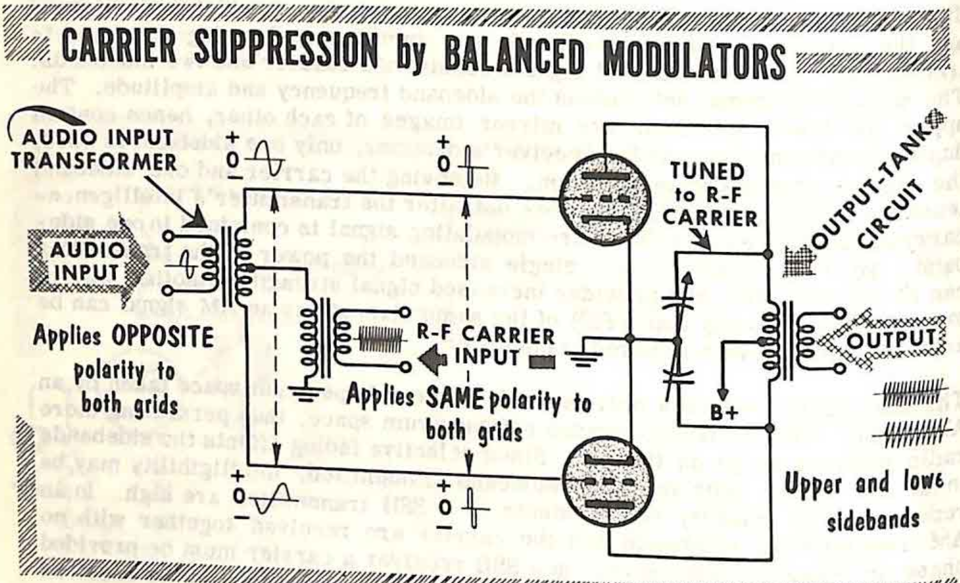
Basics of Single-Sideband Transmission

Single sideband (SSB) is a method of radio transmission in which one sideband and the carrier are suppressed; only one intelligence-bearing sideband is transmitted. Conventional AM signals consist of a carrier and two sidebands. The modulating signal determines the sideband frequency and amplitude. The upper and lower sidebands are mirror images of each other, hence contain duplicate information. At the receiver's detector, only one sideband is used; the carrier contains no information. Removing the carrier and one sideband leaves a single sideband, and does not alter the transmitter's intelligence-carrying ability because the entire modulating signal is contained in one sideband. By transmitting only a single sideband the power of the transmitter can be concentrated, and provides increased signal strength. Another way of expressing it is to say that a SSB of the same strength as an AM signal can be achieved with a lower-powered transmitter.

The SSB signal requires only one half of the r-f spectrum space taken by an AM signal. This relieves crowded r-f spectrum space, thus permitting more radio stations to go on the air. Since selective fading affects the sidebands in an AM signal, with only one sideband transmitted, intelligibility may be reduced. The stability requirements of a SSB transmitter are high. In an AM receiver the sidebands and the carrier are received together with no phase or frequency difference. In a SSB receiver a carrier must be provided for detection. A transmitter frequency shift is quickly noticed in the received signal. The SSB receiver too, must have a high order of stability, and include especially designed detector circuits.


SINGLE SIDEBAND – Saves Spectrum Space
CARRIER
Intelligence
Intelligence
Lower sideband
Upper sideband
CONVENTIONAL AM SIGNAL
(Both sides "say" the same thing)
100% MODULATION
Carrier power: 1000 watts
Total sideband power: 500 watts
Average power output: 1500 watts
Peak power = 4 times carrier power = 4000 watts
40-DB SUPPRESSION
NO CARRIER
One sideband
Intelligence
SINGLE SIDEBAND SIGNAL
ONLY 500 watts of SSB POWER gives the SAME SIDEBAND POWER

Carrier Suppression by Balanced Modulators



There are many methods of accomplishing SSB transmission, all of which require carrier suppression. To remove the carrier while still leaving both sidebands is the job of the balanced modulator.

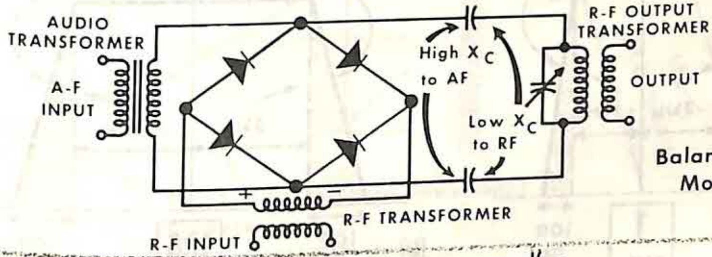
A balanced modulator using nonlinear vacuum tube amplifiers in a push-pull circuit is shown. Linear amplifiers will not mix frequencies; they will act only as amplifiers. The r-f carrier plate currents flow in equal but opposite directions to cancel each other. Thus there is no r-f carrier signal output. With the audio-modulating signal applied, the circuit acts as a conventional push-pull amplifier. The plate circuit, however, is tuned to the carrier. As a result, there is no audio output in the secondary of the plate circuit r-f transformer. Thus far, with either an r-f signal or audio signal applied, there is no output of the balanced modulator.

With both an a-f and r-f signal applied simultaneously, the circuit acts as follows: assuming that the polarity of the r-f carrier at the grid is negative at a given instant, the audio signal will have at any instant equal but opposite polarities at the secondary of the audio-input transformer. This places the modulating signal at one grid positive, and at one grid negative. The r-f and the a-f signals combine at the grid circuit. The grid having a positive a-f signal and negative r-f carrier signal will have a resultant cancellation. The grid, having a negative a-f signal and negative r-f carrier, will have the two signals add. The resultant mixing of both the r-f and a-f signals generates an output signal. The output frequency is the frequency of the carrier, plus or minus the modulating frequency. There is no carrier frequency itself, no audio frequency itself, only the two sidebands.

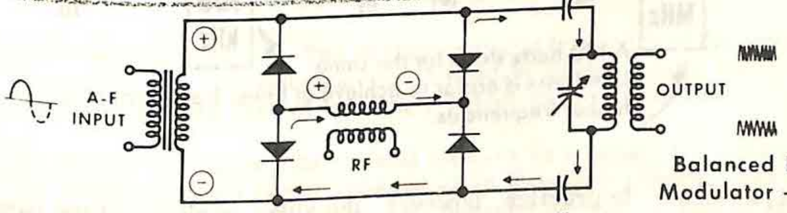
Carrier Suppression by Balanced-Bridge Modulators

A balanced modulator using a bridge rectifier circuit can provide a suppressed-carrier, double-sideband output. With only an r-f signal applied with the polarity shown, all diodes conduct, act as short-circuit, and prevent any r-f signal from getting to the output. With reversed polarity applied, the r-f signal places a positive polarity at the cathodes and a negative polarity at the plates of the diodes. The diodes do not conduct; they present an open circuit to the r-f input, and there is still no output signal. The audio modulation alone does not result in any output signal since the output-tank circuit is tuned to the r-f carrier frequency.

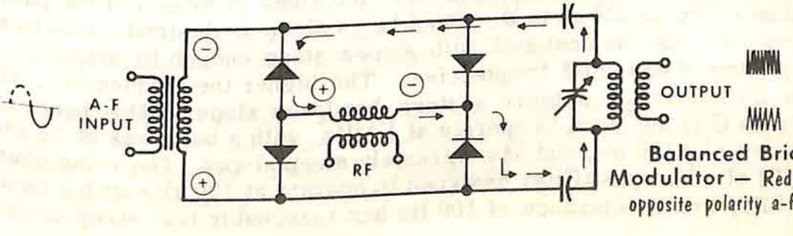
When a modulating signal and an r-f carrier signal are applied simultaneously, there is an output. The audio signal biases the diode, causing current to flow in one direction or another as determined by the polarity of the modulating signal. If the polarities of the audio and the r-f signals are as shown, the r-f carrier signal passes through the biased diodes, and provides an output signal. Reversing the polarity of the audio-signal voltage causes conduction in the opposite direction, and again provides an output signal. The modulating signal amplitude sets the diodes bias level, and modulates the r-f carrier. The output signal has no carrier, containing only sidebands. The output of a balanced modulator is a double sideband (DSB) with a suppressed carrier. A DSB signal is more efficient than a conventional AM signal because the power normally expended on the carrier can be applied to transmitting both sidebands.



Balanced Bridge Modulator



Balanced Bridge Modulator — Redrawn

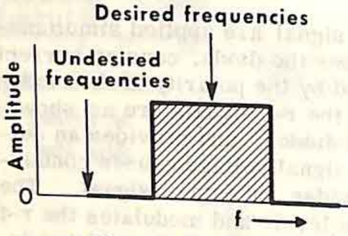


Balanced Bridge Modulator — Redrawn with opposite polarity a-f signal

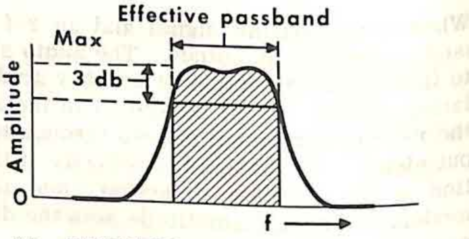
Sideband Suppression: Bandpass Filters

To obtain a SSB signal from the DSB output of the modulator, one of the sidebands is suppressed; either the lower or the upper. The two most popular methods for suppressing sidebands use filters and/or phasing circuits.

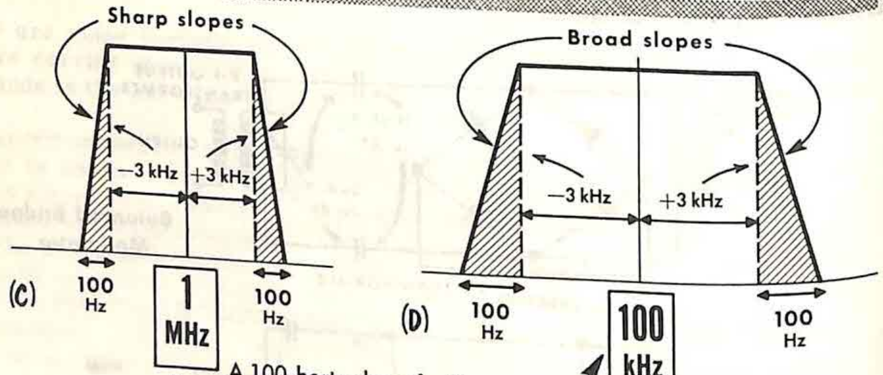
A bandpass filter passes a specific band of frequencies while rejecting all others. The requirement of such a filter is that the cutoff of the unwanted frequencies be as sharp as possible. A theoretical bandpass-filter frequency-response curve shown in A cuts off all frequencies exactly above and below



(A) IDEAL BANDPASS RESPONSE



(B) PRACTICAL BANDPASS RESPONSE



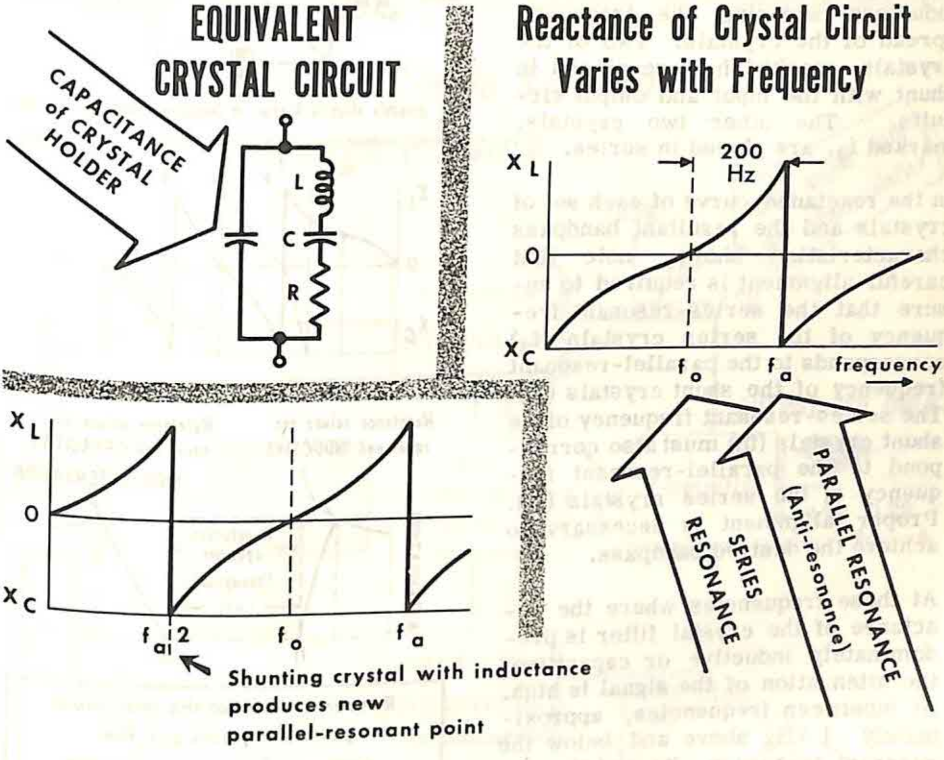
A 100-hertz slope for the same bandpass is easier to achieve at lower frequencies than at higher frequencies

the desired passband. In practice, however, the sides or slopes of the pass-band response curve as shown in B, cannot be as steep as desired. Bandpass filters, however, may be designed with slopes steep enough to achieve the desired rejection of unwanted frequencies. The higher the frequencies, the greater the difficulties to achieve a steep bandpass slope. The bandpass filter shown in C is designed to operate at 1 MHz, with a bandpass of ± 3 kHz and a tolerance of ±100 Hz, and has extremely steep slopes. The same characteristic (D) of a bandpass filter designed to operate at 100 kHz with a bandpass of ±3 kHz, and a tolerance of 100 Hz has reasonably less steep slopes.

Crystal Filters

Carefully designed, tuned L-C circuits can achieve the steep slopes required in sharp cutoff bandpass filters, but a more popular method is the use of crystals.

The crystal itself is basically a high-Q series-resonant circuit. The capacitance of the crystal-mounting device appears across the crystal to present a parallel-resonant circuit. The series-resonant frequency of the crystal alone is lower than the parallel-resonant frequency of the crystal and holder. At series resonance the circuit is neither inductive nor capacitive.


EQUIVALENT CRYSTAL CIRCUIT
CAPACITANCE of CRYSTAL HOLDER
L
C
R
Reactance of Crystal Circuit Varies with Frequency
X_L
200 Hz
0
X_C
f_o
f_a
frequency
SERIES RESONANCE
PARALLEL RESONANCE (Anti-resonance)
X_L
0
X_C
f_{a2}
f_o
f_a
Shunting crystal with inductance produces new parallel-resonant point

Below series resonance, the crystal appears as a capacitive circuit. Above series resonance the crystal appears as an inductive circuit. The parallel-resonant frequency is called the antiresonant frequency and is labeled f_a. Between the series-resonant and parallel-resonant frequencies there is a bandwidth of approximately 200 hertz.

To increase the frequency spread between the series- and the parallel-resonant frequency, an inductor is shunted across the crystal. The shunted inductance causes the crystal to appear as a parallel-resonant circuit at a frequency below series resonance.

Crystal Filters (Cont'd)

A crystal-filter circuit of the type shown is called a lattice type filter.

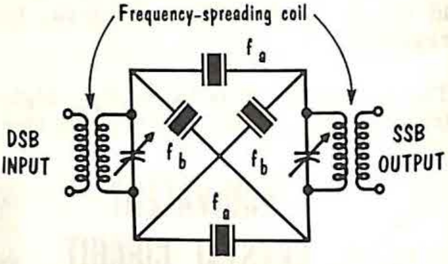
Two pairs of crystals are used; each pair may be tuned to a frequency approximately 1 kHz apart. The input and output tuned circuits act as shunt inductors widening the frequency spread of the crystals. Two of the crystals, marked f_b, are placed in shunt with the input and output circuits. The other two crystals, marked f_a, are placed in series.

In the reactance curve of each set of crystals and the resultant bandpass characteristics shown, note that careful alignment is required to ensure that the series-resonant frequency of the series crystals (f_a) corresponds to the parallel-resonant frequency of the shunt crystals (f_b). The series-resonant frequency of the shunt crystals (f_b) must also correspond to the parallel-resonant frequency of the series crystals (f_a). Proper alignment is necessary to achieve the desired bandpass.

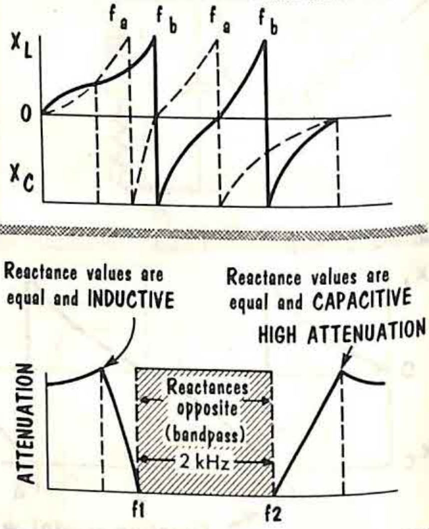
At those frequencies where the reactance of the crystal filter is predominately inductive or capacitive, the attenuation of the signal is high. At inbetween frequencies, approximately 1 kHz above and below the resonant frequency, X_L and X_C are equal, or nearly so, thereby canceling and permitting these frequencies to pass. To achieve very steep slopes of the bandpass response curve the output of one filter may be applied to a second filter.

The price paid for the sharp selection of frequencies is a loss in power known as the insertion loss of the filter. This loss is the ratio of input power to output power of the filter.

A CRYSTAL LATTICE FILTER



f_b crystals slightly higher in frequency than f_a crystals

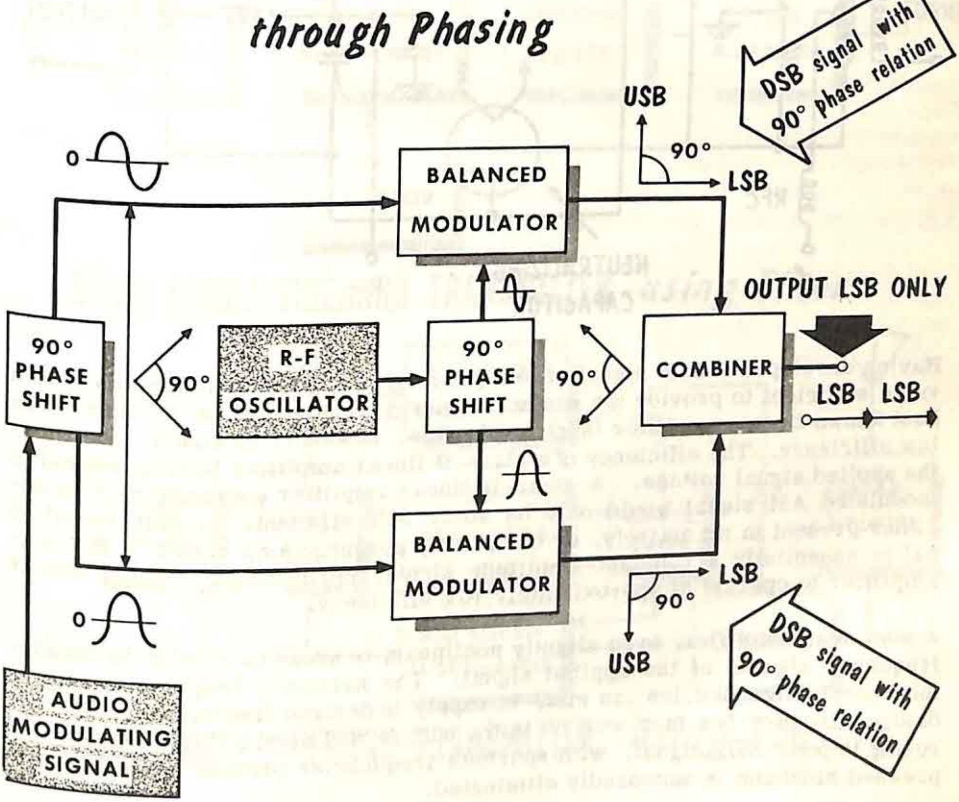


Response curve of the individual pairs of crystals and the corresponding response curve of the filter

Phasing Method

Removing a sideband by phasing is essentially done by applying out-of-phase signals to cancel each other. The modulating audio signal is applied to a phase-shifting network supplying two audio signals of equal amplitude, 90° out of phase, as shown by the accompanying vector. In addition, an r-f signal is also applied to a phase-shifting network to supply two r-f signals of equal amplitude that are 90° out of phase, as shown by the accompanying vector. The r-f and a-f signals are then applied to two balanced modulators.

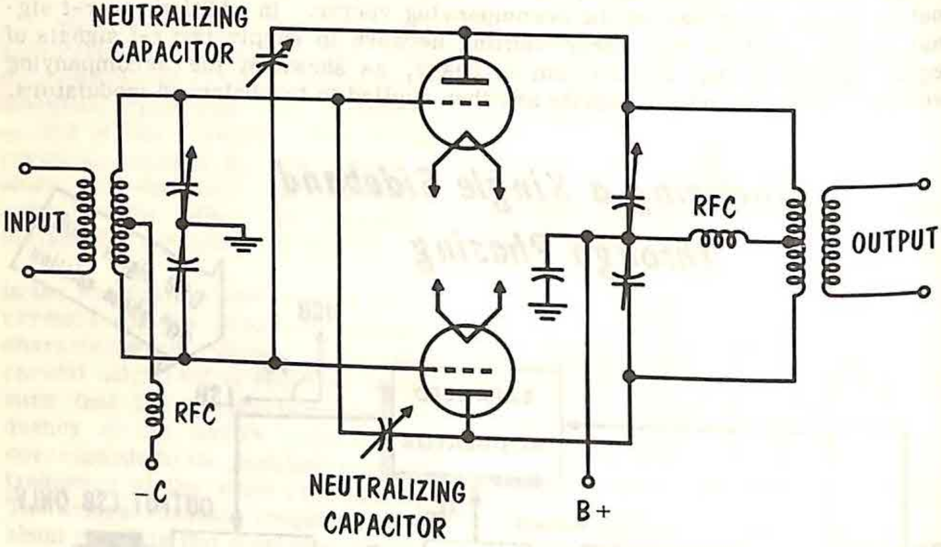
Producing a Single Sideband through Phasing



The output of the two modulator circuits consists of two DSB signals with the sidebands 90° out of phase with each other.

The two out-of-phase DSB signals are then placed in a combining circuit. The two upper sideband signals being 180° out of phase, cancel each other; the two lower sideband signals being in phase, add to produce a single sideband signal. To reverse the output to an upper sideband signal, the two out-of-phase audio signals going to the balanced modulators are reversed.

CLASS-B LINEAR AMPLIFIER for SSB AMPLIFICATION



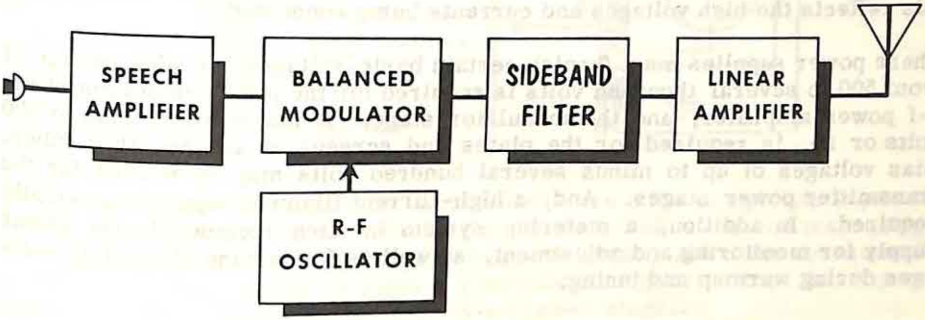
Having developed a SSB signal of low power it is necessary to amplify it to a value sufficient to provide the radiation energy required at the antenna. The best known linear amplifier is class-A; this, however, is costly, due to its low efficiency. The efficiency of a class-B linear amplifier is proportional to the applied signal voltage. A class-B linear amplifier operating with an unmodulated AM signal would only be about 35% efficient. A SSB signal is either present in its entirety, or completely absent. As a result, a SSB signal is essentially a constant-amplitude signal, permitting a class-B linear amplifier to operate at approximately 70% efficiency.

A nonlinear amplifier, even slightly nonlinear, is prone to develop harmonic-frequency signals of the applied signal. The harmonic frequencies and the fundamental frequencies can mix, to supply undesired frequencies. The undesired frequencies may well be in the suppressed sideband frequency. The result is poor SSB signal, with spurious frequencies present where the suppressed sideband is supposedly eliminated.

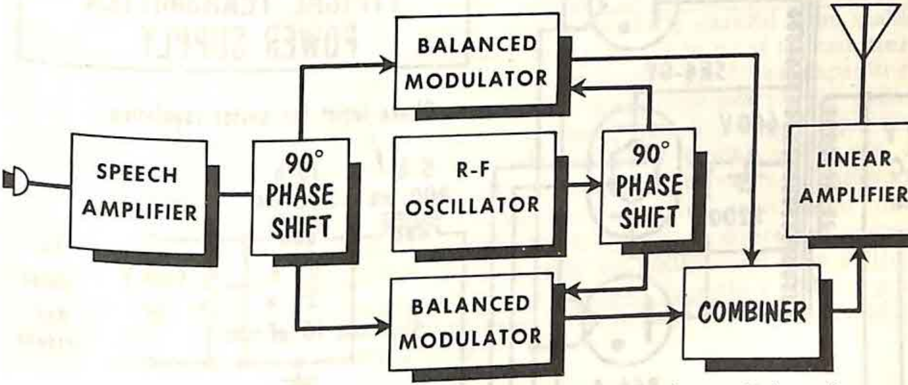
A class-A or -B linear amplifier resembles a typical class-C circuit, its main difference being in the value of grid bias. To operate class-B, the grid bias is set at cutoff; the tube amplifies only the positive-going portion of the signal. A highly-positive signal swing may cause the grid to go positive and draw grid current. When this happens, the grid circuit is no longer a high-impedance circuit. This power must come from the stage driving the linear amplifier. It is important that the driver stage be capable of supplying this power to the grid circuit. A well-designed driver will be capable of supplying at least three times the required power.

Basic SSB Transmitters

Special circuits are available to permit SSB reception with the least amount of difficulty. However, any good standard type commercial receiver with high stability, good band spread, and a beat-frequency oscillator, can be used to receive SSB. To receive a SSB signal, the prime consideration is that a carrier be reinserted to beat with the SSB signal for detection. In a commercial receiver this can be done with the bfo used for code reception. For proper detection the bfo signal level should be at least 10 times as strong as that of the received signal. Since the bfo level is fixed, and not as high as desired in the average receiver, the signal level can be reduced by lowering the r-f gain of the receiver.



BASIC SINGLE-SIDEBAND TRANSMITTER *using Filters*



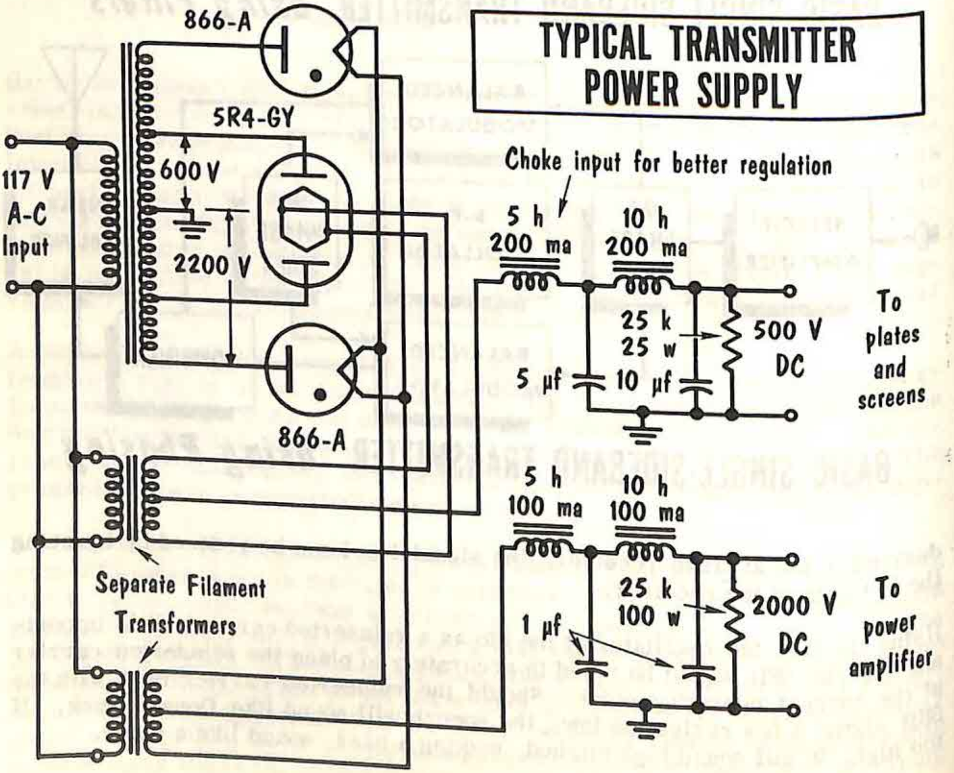
BASIC SINGLE-SIDEBAND TRANSMITTER *using Phasing*

Using the injected oscillator of the bfo as a reinserted carrier, it is important that the SSB signal be tuned in accurately to place the reinserted carrier at the correct operating point. Should the reinserted carrier beat with the SSB signal a few cycles too low, the speech will sound like Donald Duck. If too high, it will sound high pitched, making a bass sound like a tenor.

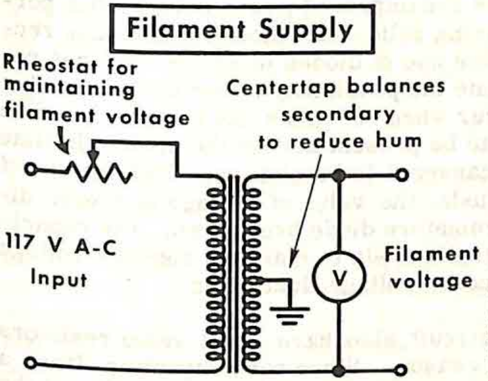
Transmitter Power Supplies

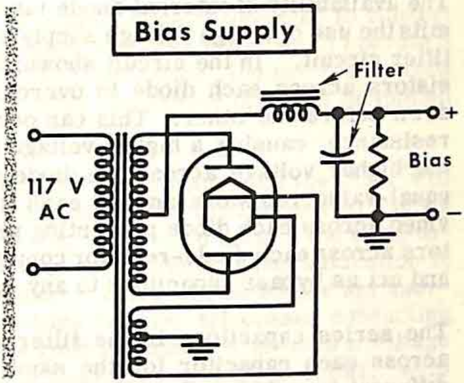
Power-supply circuits used in transmitters are basically the same as those used in receivers except for voltage and current considerations, and the many special types of controls. Half-wave, full-wave, and bridge-rectifier circuits are used. However, the rectifier tubes are much larger, being able to withstand many thousands of volts. Where large amounts of plate and screen currents are required, mercury-vapor tubes are used. These furnish high-power supply currents and produce small voltage drops across the rectifier tubes themselves. In transmitter power supply the power transformers are quite large, as are the filter capacitors, chokes, and insulators. All this reflects the high voltages and currents being consumed.

These power supplies must furnish certain basic voltages. A high voltage of from 500 to several thousand volts is required for the plate and screen of the r-f power amplifier, and the modulator stage. A low voltage of up to 500 volts or so, is required for the plates and screens of all the other tubes. Bias voltages of up to minus several hundred volts may be needed for the transmitter power stages. And, a high-current filament supply is generally required. In addition, a metering system is often included in the power supply for monitoring and adjustment, as well as for turning off certain voltages during warmup and tuning.



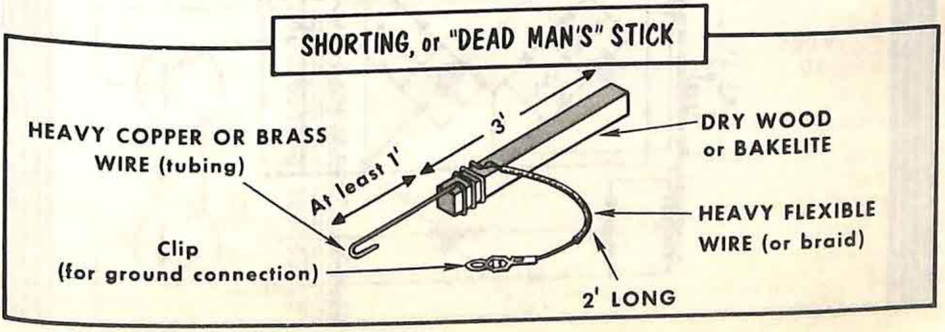
Transmitter Power Supplies (Cont'd)


Filament Supply
Rheostat for maintaining filament voltage
Centertap balances secondary to reduce hum
117 V A-C Input
V
Filament voltage



The filament and bias supply for transmitters are often completely separate units. The filament supply often has a means of adjusting and measuring, since a slight decrease in filament voltage can greatly affect the operation of a tube. The bias supply is often a conventional supply, except that it provides a negative voltage for the r-f and a-f power stages.

Most transmitters operate with plate voltages of from 250 volts to many thousands of volts. Contact with these voltages can cause serious shock or even death. It is necessary, therefore, to be especially careful when making transmitter adjustments. When the power is turned off in most transmitters, the bleeder and voltage-divider resistors discharge the filter capacitors. However, one or more of these resistors may open, and prevent the capacitors from discharging. If body contact is made with a charged capacitor, the capacitor can discharge through the body and cause shock, burns, or, as mentioned, death. Most transmitters with an output of 100 watts or more are equipped with switches, relays, or timing devices which open the primary circuits to high-voltage circuits whenever the transmitter doors are opened. However, any of these protective devices may be faulty, and then a "live" transmitter is even more dangerous than a charged capacitor. As a precaution, make sure there is no high voltage present, and discharge the high-voltage capacitors with a shorting stick.


SHORTING, or "DEAD MAN'S" STICK
HEAVY COPPER OR BRASS WIRE (tubing)
3'
At least 1'
DRY WOOD or BAKELITE
HEAVY FLEXIBLE WIRE (or braid)
Clip (for ground connection)
2' LONG

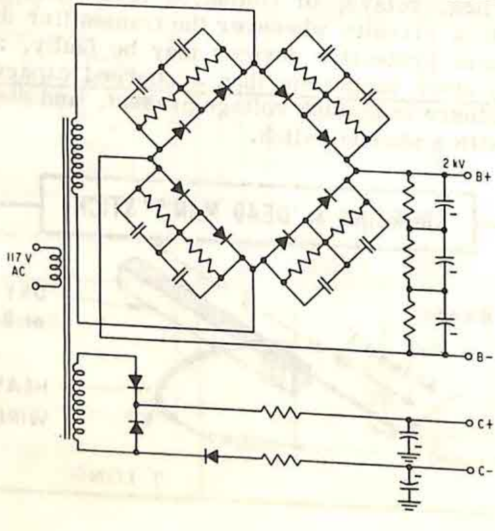
Transmitter Power Supplies (Cont'd)

The availability of external anode tubes and improved power output tubes permits the use of a high voltage supply using solid-state diodes in a bridge rectifier circuit. In the circuit shown, the use of diodes in series requires resistors across each diode to overcome the possibility of one diode breaking down before the other. This can occur when one diode has a higher junction resistance, causing a higher voltage to be present across the diode. In time the higher voltage across the diode causes it to breakdown. With the use of equal-value resistors across each diode, the value of voltage is evenly divided across each diode preventing premature diode breakdown. The capacitors across each diode-resistor combination help to maintain constant voltage and act as bypass capacitors to any sudden voltage fluctuation.

The series capacitors in the filter circuit also have equal value resistors across each capacitor for the same reason. Since each capacitor offers a different impedance, the voltage drop across each would not be equal, and the capacitor with the highest impedance would have the highest voltage drop across it. In time this capacitor could prematurely break down. With equal value resistors across each capacitor, the voltage is evenly divided, preventing this premature breakdown. The resistors also act as bleeders to aid in voltage regulation, and also as a safety feature in discharging the capacitors when the a-c power is switched off.

The bias voltage power supply provides a full-wave rectified positive voltage output that can be used for screen grid voltage. The half-wave rectified negative voltage output is utilized for control grid bias supply.

TRANSMITTER POWER SUPPLY PROVIDING HIGH VOLTAGE PLUS SCREEN GRID AND BIAS VOLTAGES



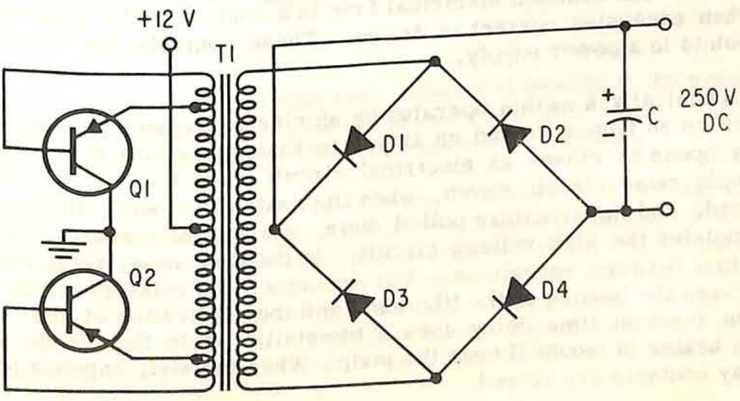
D-C to D-C Converter Power Supply

A power supply for mobile (automotive or marine) use is designed to convert the low-voltage d-c of a battery to the higher voltages required to operate a transmitter or transceiver. As shown in the illustration, the two transistors and the transformer form a d-c to a-c inverter, the output of which is applied to a bridge rectifier to form a d-c to d-c converter.

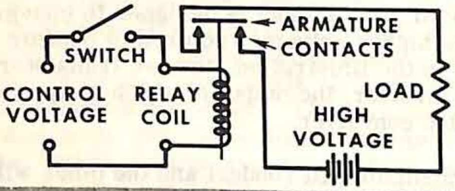
With the battery voltage applied, one transistor will conduct and the other will go into cutoff. Assume Q1 conducts, the expanding field in the primary of T1 caused by the conduction of Q1 will develop a forward bias in the base-to-emitter winding of Q1 that maintains Q1 in conduction. When saturation is reached the magnetic field becomes stationary; there are no longer any moving lines of force to maintain the induced-bias voltage, Q1 ceases conducting and the magnetic field collapses. As the field collapses it induces a voltage in the opposite polarity that places Q2 in conduction and Q1 in cutoff. With Q2 conducting through the opposite half of the primary of T1, the magnetic field reverses polarity. As the field reaches saturation the cycle repeats; Q2 becomes cut off, Q1 conducts, and the magnetic field about the primary of T1 reverses polarity. Thus Q1 and Q2 act as an oscillator, with the voltage on the secondary of T1 appearing as a sine wave.

The high-value a-c voltage developed at the secondary of T1 is applied to a bridge rectifier consisting of four diodes. Assume the polarity at the secondary of T1 was such that the top of the winding was positive and the bottom negative. The electron flow would be through the cathode to anode of D4 to charge the negative plate of the charging capacitor C, driving the electrons off the positive terminal. With the polarities at the secondary reversed, the electron flow would be through the cathode to anode of D2 to again charge the negative plate of charging capacitor C, driving the electrons off the positive plate and through the cathode to anode of D3 to the positive terminal. Thus we have a d-c to d-c converter changing 12 volts d-c to approximately 250 volts d-c.

DC-to-DC Converter Power Supply

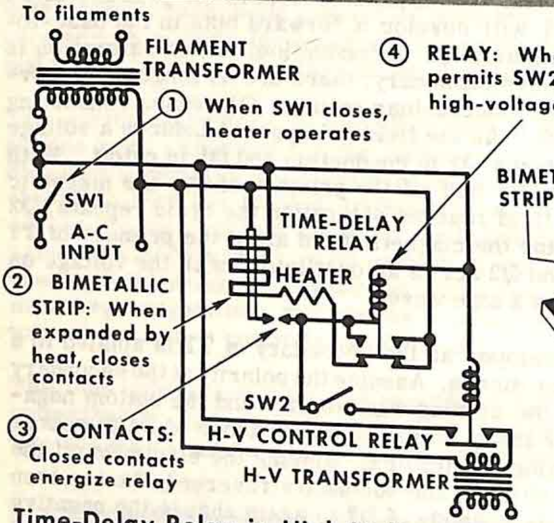


Transmitter Controls



BASIC RELAY CIRCUIT

When switch is closed relay is energized, and load circuit is completed



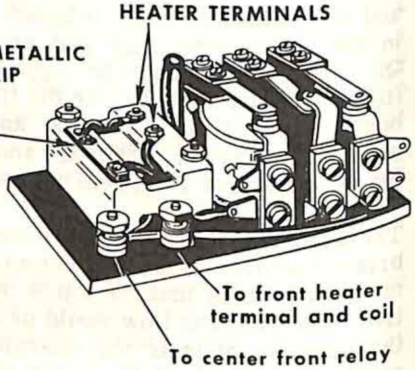
① When SW1 closes, heater operates

② BIMETALLIC STRIP: When expanded by heat, closes contacts

③ CONTACTS: Closed contacts energize relay

④ RELAY: When energized, permits SW2 to close high-voltage relay

Time-Delay Relay in High-Voltage Circuit



Time-Delay Relay

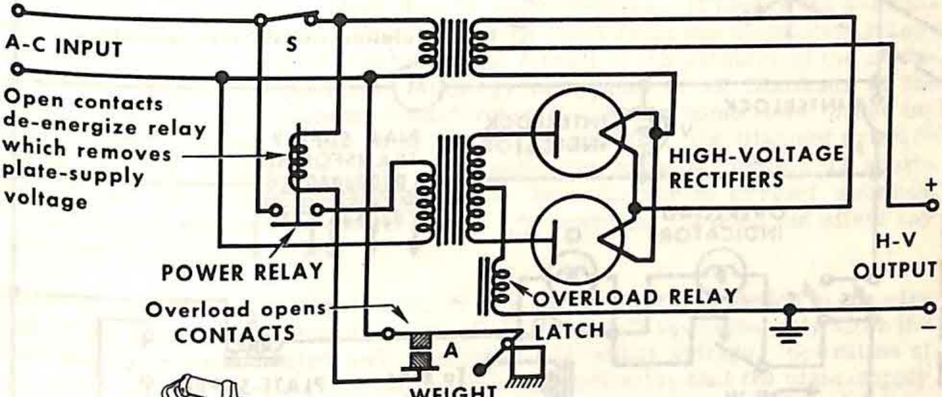
A number of devices are associated with power supplies to control and direct their functions, and to serve as protection to equipment and personnel. These controls take the form of key switches, circuit breakers, relays, panel-interlock switches, and time delays. Controls also operate signal devices that flash a light or sound an alarm when voltages and currents exceed a rated value. The common electrical fuse is a control device that opens the circuit when excessive current is drawn. These controls are connected at various points in a power supply.

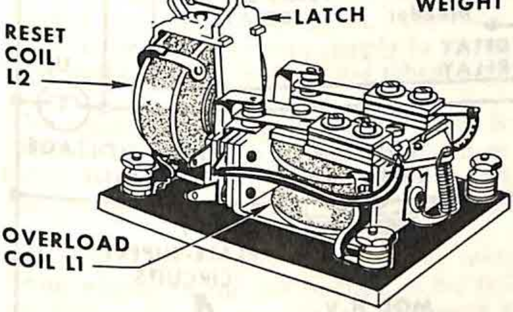
A relay is basically a switch operated by an electromagnet. It consists of a coil wound on an iron core and an armature that operates a set of contacts. The relay opens or closes an electrical circuit when the coil is energized. In the simple relay-circuit shown, when the switch is closed, the relay coil is energized, and the armature pulled down, closing the contacts. This, in turn, completes the high-voltage circuit. In the time-delay relay there is a definite time between operations. For instance, the relay provides a time delay between the heating of the filaments and the application of high voltage. A common form of time delay uses a bimetallic strip that bends as it is heated. A heater is mounted near the strip. When the strip expands from the heat, relay contacts are closed.

Transmitter Controls (Cont'd)

An overload relay is a protective device that opens a circuit automatically when the current through it exceeds a certain established value. It is usually a d-c plunger relay in which the magnetic field of the relay coil acts upon a plunger. When the current becomes too great, the relay contacts open. A latch is usually included in the relay to keep the circuit open after the relay is energized, preventing the circuit from opening and closing repeatedly while the overload exists. The relay can have a mechanical release, or reset button, to restore it to operation after the overload has been removed. In the drawing, L1 is the overload coil, connected usually in the negative lead of the circuit being protected. L2 is the reset coil and, when energized, resets the mechanical latch after the relay has been energized.

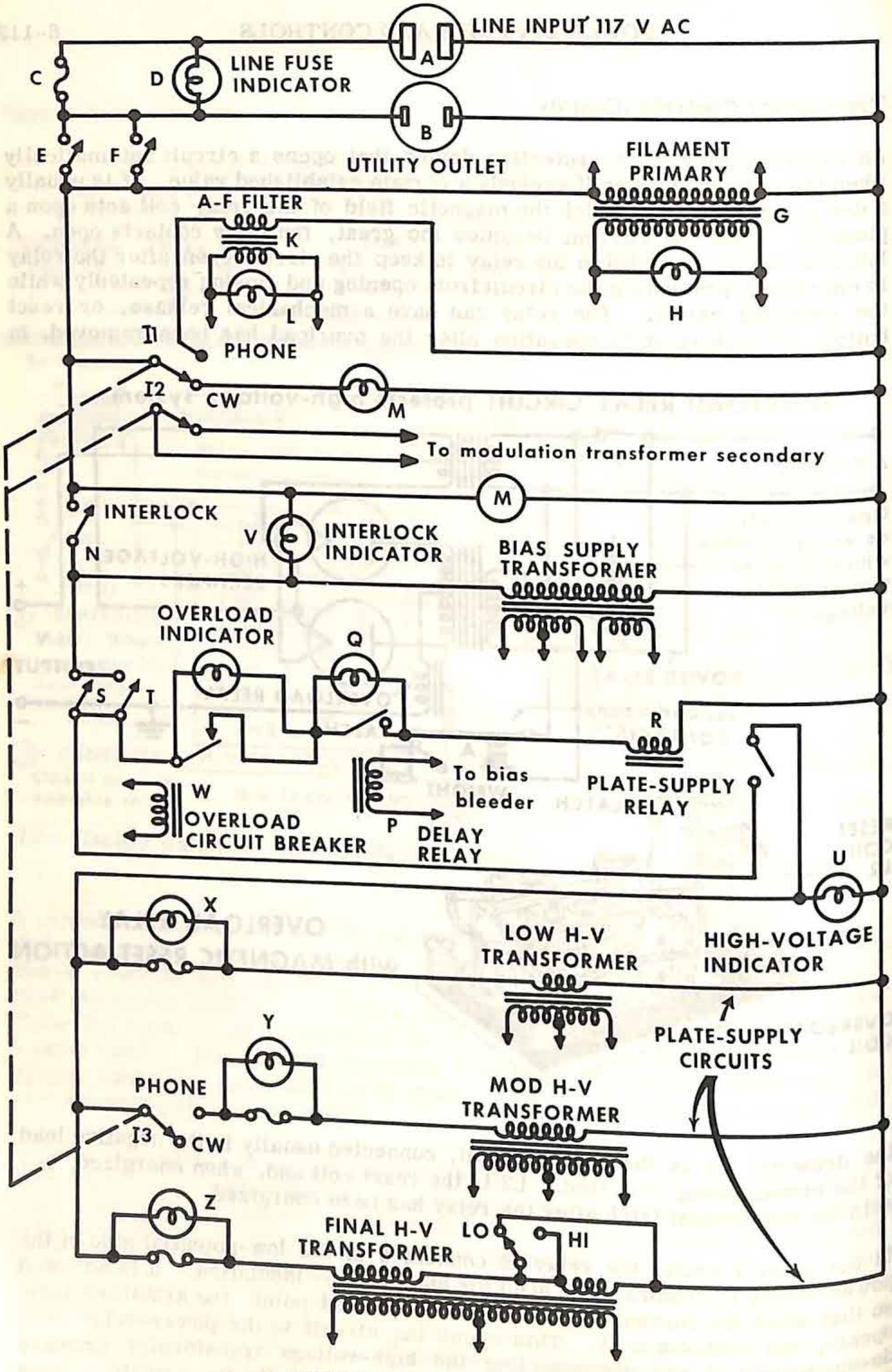
OVERLOAD RELAY CIRCUIT protects high-voltage system





OVERLOAD RELAY with MAGNETIC RESET ACTION

In the relay circuit, the relay is connected in the low-potential side of the power supply to eliminate the need for high-voltage insulation. It is adjusted so that when the current reaches a predetermined point, the armature lifts, opening the contacts at A. This opens the circuit to the power-relay coil, de-energizing it and disconnecting the high-voltage transformer primary from the a-c input line. The weighted latch prevents the armature from falling and closing the contacts before the overload has been corrected.



TYPICAL CONTROL SYSTEM

Transmitter Control System

On the opposite page we see a complete transmitter control system, including line fuses, indicator lamps, and protective devices. At A, on top, is the basic 117-volt a-c power input. B represents a utility outlet that is not affected by subsequent switching. The input circuit is fused by C, with indicator lamp D lighting when C is open.

Filament switches E and F are connected in parallel. F energizes filament transformer G, and E supplies voltage to the remainder of the circuit, as required. Indicator lamp H, across the filament transformer secondary, lights when the filaments have been turned on. Ganged switch I1, I2, and I3, is the phone-CW switch. When it is in phone position, I1 closes the a-f filament transformer primary, I2 removes the short from the modulation transformer secondary, and I3 completes the circuit to the primary of the modulator high-voltage transformer. Voltage is applied to all filaments of the audio section through filament transformer K. At the same time, phone indicator lamp L lights. If the switch is in CW position, the filament primaries of the a-f section are open, and indicator lamp M lights. I2 short-circuits the secondary of the modulation transformer to prevent spurious oscillations in the modulation circuit on CW position. I3 does not affect any circuitry in the CW position.

Meter M is a line voltage indicator. N is a safety interlock-switch in the circuit of the bias-supply transformer. Delay-relay P operates only after the bias supply is fully heated and delivering full output voltage. Operation of the relay shorts the bias indicator lamp Q, indicating that the plate-supply relay R is ready for operation. The time required for the operation of delay-relay P permits the bias supply to warm up enough so that it is safe to apply plate voltage to the r-f and a-f tubes.

With relay P closed, plate-supply relay R can be energized with the transmit-receive switch S (or T, an extension of the switch for remote operation). Relay R turns on all plate voltages, and lights the high-voltage indicator U. The transmitter is now ready for operation.

Indicator lamp V lights whenever the interlock switch is open. The interlock opens whenever the top or back of the transmitter has been removed, or has not been replaced securely. Whenever the interlock is open, all high voltages are removed from the transmitter, for the indicator lamp has enough resistance to prevent the bias power supply from operating.

W is an overload circuit breaker. Whenever the plate current to the final amplifier goes too high, exceeding the critical value for which the circuit breaker has been set, the circuit breaker operates. It opens the plate-supply relay circuit and causes all high-voltage stages to become inoperative. X, Y, and Z, are fuse-indicator lamps. They light whenever excess current opens the fuses associated with them.

The lo-hi switch in the primary of the final high-voltage transformer makes it possible to change from high to low power for tuning and testing purposes. For standby operation, only switch S (and/or T) has to be operated.

Transceiver

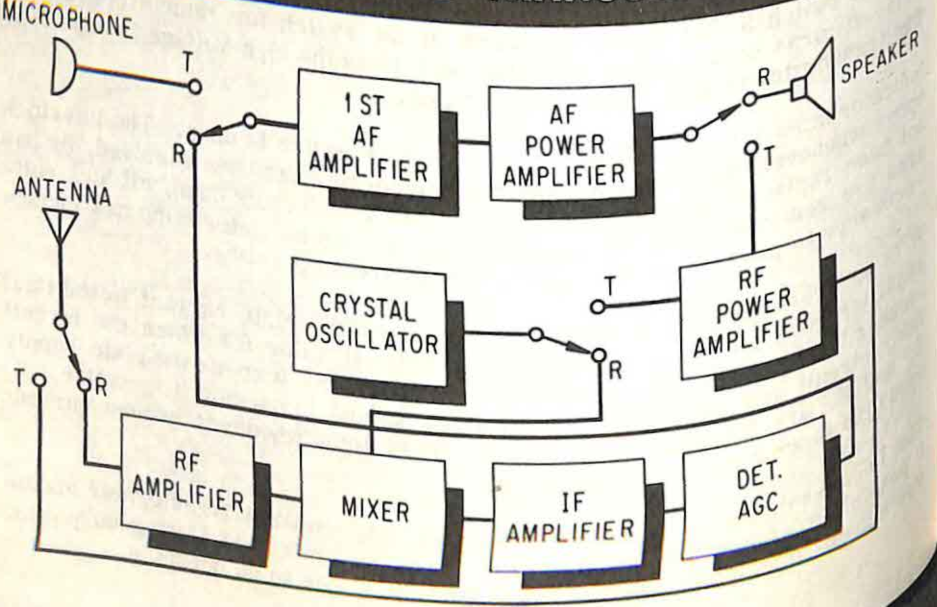
A "transceiver" is a combined transmitter and receiver in which some of the circuits are used in both the transmitter and the receiver circuitry. These dual-use circuits are switched between the transmitter and receiver by either a manual switch or a relay containing multiple switches.

The block diagram illustrates a Citizens' Band transceiver circuit using a manual Transmit-Receive switch. With the switch in the Receive position the antenna is applied to the r-f amplifier of the receiver. The crystal oscillator used to set the desired channel frequency has its output applied to the mixer; thus the crystal oscillator acts as the receiver local oscillator. The detected output is applied to the 1st AF amplifier then the AF power amplifier to feed the detected audio signal to the loudspeaker.

With the switch set in the Transmit position the output of the microphone is applied to the 1st a-f amplifier and the a-f power amplifier. The output of the a-f power amplifier is applied to the r-f power amplifier as the audio modulating signal. The crystal oscillator output is also applied to the r-f power amplifier to set the output frequency. The modulated AM signal set on the channel frequency by the crystal oscillator is applied directly to the antenna.

In the circuit shown, the antenna is switched between the receiver and transmitter; in addition, the crystal oscillator and audio amplifiers are also switched and used as both receiver and transmitter circuits to create a "transceiver."

CITIZENS BAND TRANSCEIVER



SUMMARY

Varying the inductance or capacitance in an oscillator in accordance with an audio signal produces FM.

In phase modulation, the instantaneous phase of the signal is varied by the modulating signal.

A change in phase is equivalent to an instantaneous change in frequency.

In a phase-modulation system, the equivalent frequency deviation is proportional to the frequency of the modulating signal.

When the carrier frequency is varied directly, the process is called direct FM.

When the carrier is varied indirectly, the process is called indirect FM.

In single sideband transmission, the frequencies produced by the process of modulation on one side of the carrier are transmitted, and those on the other side are suppressed.

A crystal filter is a selective circuit using a filter that discriminates against all signals except those at the center frequency of the crystal.

A linear amplifier develops an output directly proportional in amplitude to that of the input signal.

In single sideband, since the carrier and one set of sidebands are not present in the output, a single sideband signal occupies less than half the spectrum space of a conventional AM signal.

In the filter method of sideband suppression, one sideband is removed by quartz-crystal filters or electromechanical filters.

In the phasing method of sideband suppression, the undesired sideband is removed by a process of phase shifting and balanced circuits.

The balanced modulator is desirable for single sideband applications because the balanced circuitry permits the carrier signal to be canceled out so that it does not appear in the output.

Transmitter power supplies differ little from conventional receiver supplies except in the components involved, which must handle much higher voltages and currents.

Transmitters use various types of relays to control the application of power to various circuits. All controls are designed for the protection of transmitter components, and for the safety of the operator.

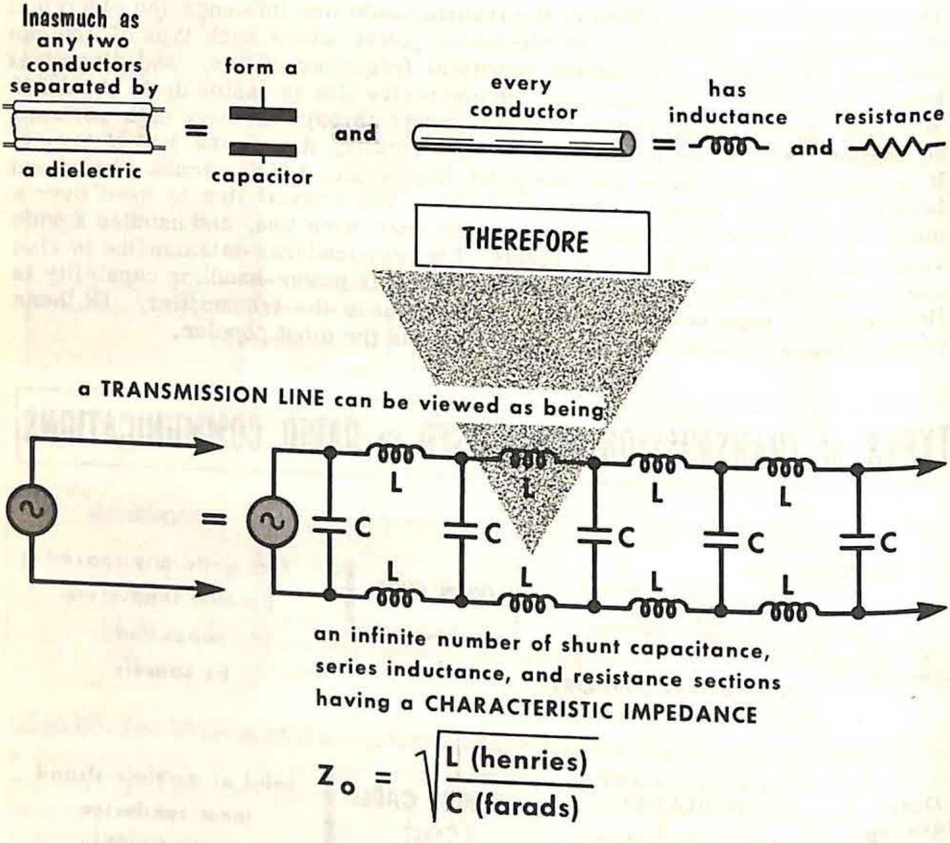
REVIEW QUESTIONS

1. Explain the difference between direct and indirect FM.
2. Explain the difference between frequency and phase modulation.
3. Explain how FM is produced using a reactance-tube modulator.
4. How does a single sideband signal differ from a conventional AM signal?
5. How is the carrier suppressed by the balanced modulator?
6. Explain the filter method of sideband suppression.
7. Explain the phasing method of sideband suppression.
8. What is an advantage of single sideband transmission over double sideband transmission?
9. What is the function of a linear amplifier?
10. What is the basic difference between transmitter and receiver power supplies?
11. What is the function of a transmitter control system?
12. What methods are used to prevent a transmitting tube from overheating?

Inductance and Capacitance in Transmission Lines

When a d-c voltage or a low-frequency a-c voltage (say, 60 Hz) is applied to two conductors of reasonable length which terminate in a resistive load, the voltage "sees" the total resistance of the circuit.

In an infinitely-long r-f transmission line, however, energy fed to it will travel down the line and be completely absorbed. We think of the two long parallel conductors as forming a capacitance; the current-carrying conductors possess the property of inductance everywhere along the line. The same conductors also possess resistance, but this property is disregarded. Unlike the conventional circuit approach where capacitance and inductance are "lumped," capacitance and inductance in the infinitely-long transmission line are distributed throughout the length of the line. The distributed properties are apportioned into 1-foot lengths. The line can then be said to have, say, 30 micromicrofarads (μμf) per foot, and 0.15 microhenries (μh) per foot. An infinite number of sections of fixed C and L are assumed as making up the line, each section being identical.

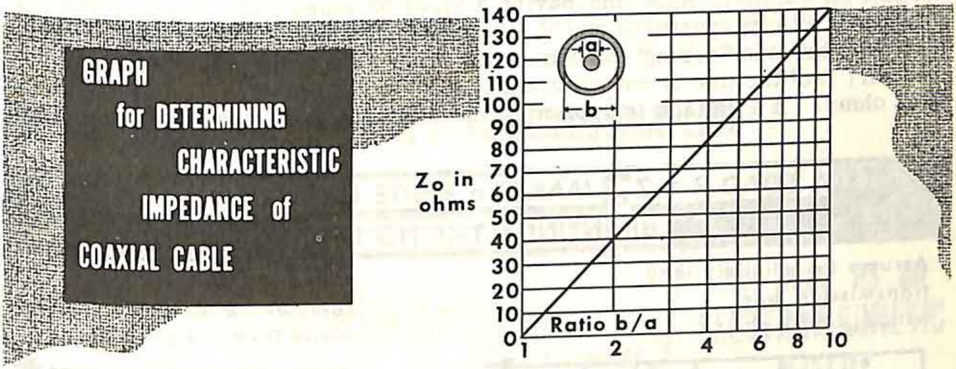

Inasmuch as any two conductors separated by
a dielectric
=
form a
capacitor
and
every conductor
has inductance
=
and
resistance
THEREFORE
a TRANSMISSION LINE can be viewed as being
=
L
C
an infinite number of shunt capacitance, series inductance, and resistance sections having a CHARACTERISTIC IMPEDANCE

$$Z_o = \sqrt{\frac{L\ (\text{henries})}{C\ (\text{farads})}}$$

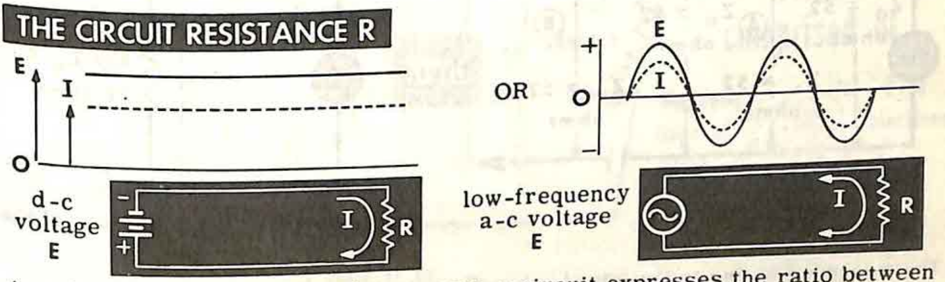
Characteristic Impedance of an Infinitely-Long Transmission Line

The shunt C and series L in each transmission line section comprise an impedance called the characteristic or surge impedance (Z_o) of the line. Z_o is purely resistive, and constant for any given line.

Your study of a-c electricity taught that Z varies with frequency. This is not so with the r-f transmission line; here, Z_o is a fixed quantity, whose ohmic value is determined by the physical construction of the line. Whereas the voltage applied to a low-frequency circuit "sees" the total impedance Z of the circuit, the r-f voltage applied to the infinitely-long transmission line "sees" only the characteristic impedance Z_o at the input of the line. The current anywhere in the circuit is proportional to the instantaneous voltage at that particular point. If the applied voltage is 100 volts at one point, and the current is 1.92 ampere, $Z_o = 100/1.92 = 52$ ohms.

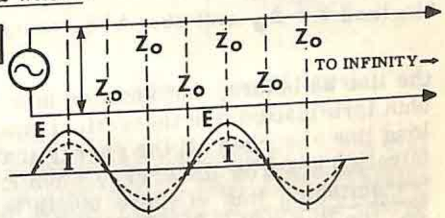

GRAPH for DETERMINING CHARACTERISTIC IMPEDANCE of COAXIAL CABLE

THE CIRCUIT RESISTANCE R



in a d-c circuit or in a low-frequency a-c circuit expresses the ratio between voltage E and current I in the circuit as a whole.

THE CHARACTERISTIC IMPEDANCE Z_o of a theoretically infinitely long transmission line expresses the ratio between E and I at each point in the circuit, rather than in the circuit as a whole.

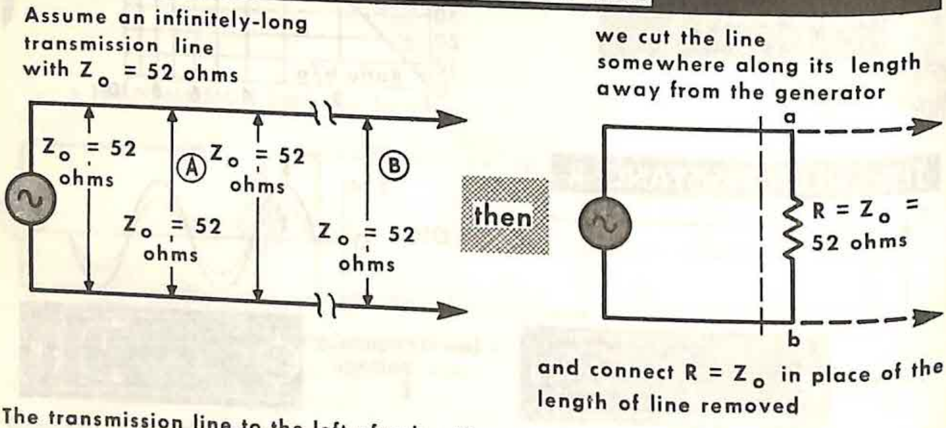


Terminating the Transmission Line

The infinitely-long r-f transmission line theoretically establishes the condition whereby a voltage applied to the line becomes energy which moves down the line never to return. When this happens, the current and voltage equivalent of the electromagnetic energy are in phase everywhere in the line. However, the infinitely-long line does not exist. Every practical transmission line is of finite length. How can such a line be made to perform like the infinitely-long line?

Imagine an infinitely long line having a Z_0 of 52 ohms to be divided (but not separated) into two parts, A and B. A voltage is applied to this line. It travels down the line "seeing" 52 ohms everywhere along its path. Now imagine that part B of the line is cut off and replaced by a resistance equal to the Z_0 of 52 ohms. If a voltage is applied to the line, the energy will advance down the line as before, not knowing how long the line is. Then it reaches the 52-ohm termination (the theoretical equivalent of part B). Just as the infinitely-long line absorbed all the energy traveling down the line, so the 52-ohm termination absorbs the energy when it reaches the load. In other words, if a transmission line of finite length is terminated in a resistance equal to its Z_0, the line will, regardless of length, demonstrate all the properties of the infinitely-long line. Such a line is called a terminated line. It transfers energy from the input to the load, with only slight loss of energy in the line. Whatever decrease in energy level (attenuation) does occur is the result of the R of the conductors as well as leakage in the dielectric that separates the two conductors. Substantially no losses are due to the characteristic impedance because it does not produce a power loss.

A LOAD $R = Z_o$ MAKES a FINITE LINE BEHAVE LIKE an INFINITELY-LONG LINE


Assume an infinitely-long transmission line with Z_o = 52 ohms
Z_o = 52 ohms
Ⓐ
Z_o = 52 ohms
Ⓑ
Z_o = 52 ohms
Z_o = 52 ohms
then
we cut the line somewhere along its length away from the generator
a
$R = Z_o$ = 52 ohms
b
and connect $R = Z_o$ in place of the length of line removed

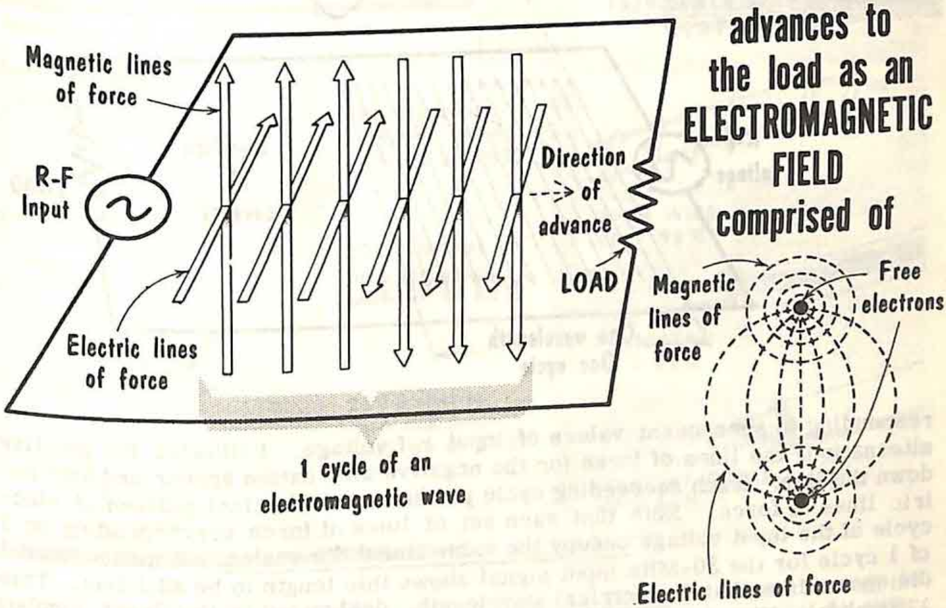
The transmission line to the left of a-b will never "know" that section Ⓑ was removed.

The load $R = Z_o$ will absorb the energy exactly as the infinitely-long line would.

The R-F Transmission Line Transports Electromagnetic Energy

In the d-c circuit and the low-frequency a-c circuit energy is conveyed by the motion of charge (current). Referring back to the distributed L and C which make up the transmission line, applying an r-f voltage to the input causes current to flow into the line – into the first "section" of the line. One result is the creation of encircling magnetic lines of force around the free electrons which move as current in each conductor. The two fields combine in the space between the conductors, producing a composite field. At the same time, electric lines of force terminating on the moving charges in each of the conductors appear in the space between the conductors. So we have magnetic and electric lines of force, the two at right angles, occupying the space between the two conductors. The two fields combined are called an electromagnetic field. You must visualize the two sets of lines of force (the electromagnetic field) appearing first at the input to the line, then advancing down the line from one imaginary section to the other, carrying the energy with them. During each half cycle, the current in each of the conductors reverses its direction, as do the electric and magnetic lines of force. All the while the electromagnetic field they form advances away from the input of the line. Thus, current flow in a terminated transmission line can flow in opposite directions at many points, but the electromagnetic energy can be advancing in one direction only.

IN the OPERATION of the R-F TRANSMISSION LINE



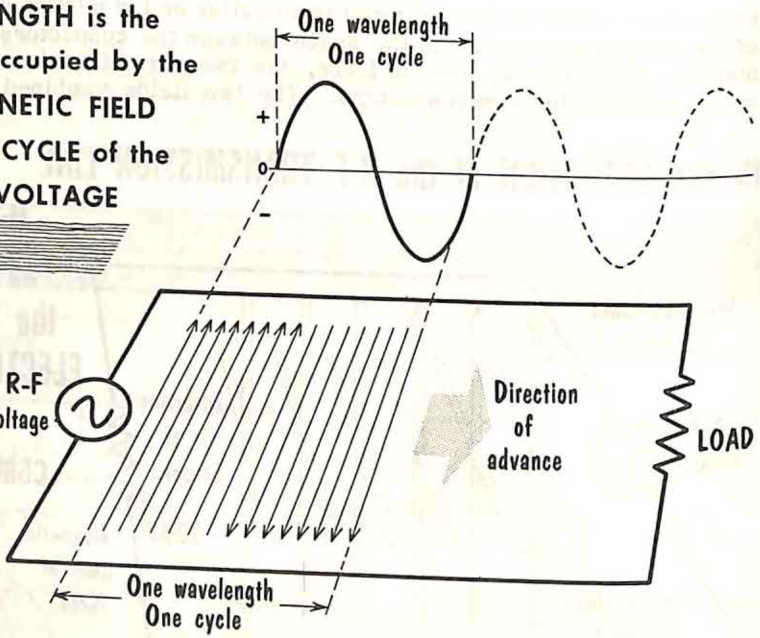
the energy advances to the load as an ELECTROMAGNETIC FIELD comprised of

Electrical Wavelength

Let us take a look at the electromagnetic field generated by a 30-MHz r-f voltage applied to the terminated transmission line. (For convenience, only the electric component of the field is shown.)

The first line of electric force appears with the first increment of input voltage and starts moving down the line, followed by the other lines of force corresponding to subsequent values of input r-f voltage. Following the positive alternation, the lines of force for the negative alternation appear and advance down the line. Each succeeding cycle produces the identical pattern of electric lines of force. Note that each set of lines of force corresponding to 1 cycle of the input voltage occupy the same lineal dimension. A measurement of 1 cycle for the 30-MHz input signal shows this length to be 32.1 feet. This dimension is called 1 electrical wavelength, designated by the Greek symbol λ (lambda). Wavelength is related to both the electric and magnetic components of the field created by each cycle; the dimension is the same with both components present. A definition of 1 wavelength could be "the lineal dimension occupied by the electric lines of force created by all the amplitude variations of voltage in 1 cycle." The length of 1 electrical wavelength arises from a fixed relationship between velocity of the field (wave) in whatever medium in which it is traveling, and the frequency of the voltage. It is

ONE WAVELENGTH is the DIMENSION occupied by the ELECTROMAGNETIC FIELD for a SINGLE CYCLE of the APPLIED R-F VOLTAGE



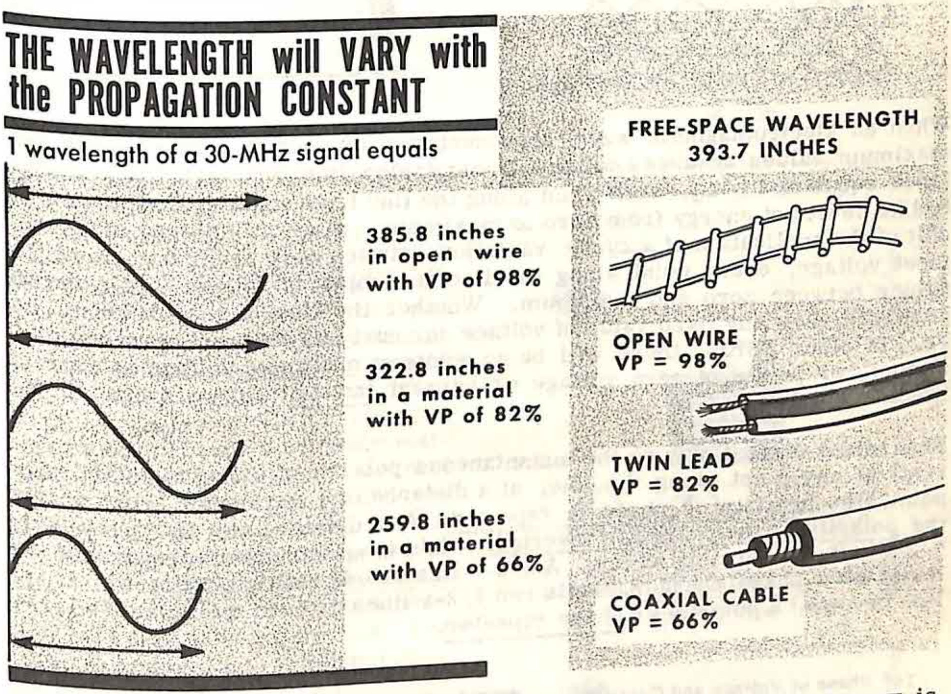
$$\text{wavelength } (\lambda) \text{ in meters} = \frac{\text{velocity of the energy in meters per second}}{\text{frequency in hertz}}$$

Electrical Wavelength and Velocity of Propagation

The reference for all velocities of electromagnetic radiations is the velocity of light in free space: 299,744,000 (usually stated as 300,000,000) meters per second, or 984 feet per μsec. Using the above velocity, the wavelength of a 30-MHz wave in free space is

$$\text{one electrical wavelength (in meters)} = \frac{300,000,000}{30,000,000} = 10 \text{ meters}$$

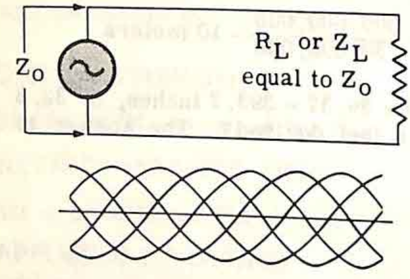
With 1 meter = 39.37 inches, 10 meters = 10 x 39.37 = 393.7 inches, or 32.8 feet. How was the previous figure of 32.1 feet derived? The answer is simply that the velocity of propagation (VP) of electromagnetic energy is most rapid in free space, and is slowed down when advancing in all other physical media. A transmission line is such a medium; the VP is lower in a transmission line than in free space. Different kinds of transmission lines bear different VP constants. When stated as a number, it is a percentage, with 100% being the velocity of light. Having determined that 1 wavelength of a 30-MHz voltage in space is 32.8 feet, 98% of this length (in an open-wire line) is 32.8 x .98 = 32.1 feet. An electrical wavelength for 60 Hz = 3100 miles. The lower the velocity the shorter the electrical wavelength for any given frequency. When a transmission line is spoken of as being so many wavelengths long, electrical wavelength is meant with the velocity of propagation already taken into account.


THE WAVELENGTH will VARY with the PROPAGATION CONSTANT

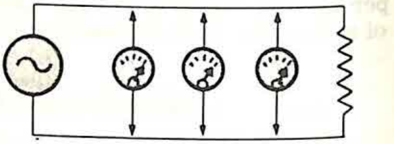
1 wavelength of a 30-MHz signal equals
FREE-SPACE WAVELENGTH 393.7 INCHES
385.8 inches in open wire with VP of 98%
322.8 inches in a material with VP of 82%
259.8 inches in a material with VP of 66%
OPEN WIRE VP = 98%
TWIN LEAD VP = 82%
COAXIAL CABLE VP = 66%

Transmission Lines Terminated in Characteristic Impedance

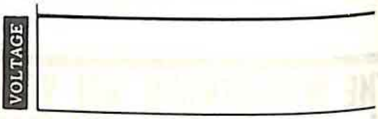
WHEN A PROPERLY TERMINATED LINE of any length is subject to a wave of energy. all points along it are subject to all values of voltage and current



AND



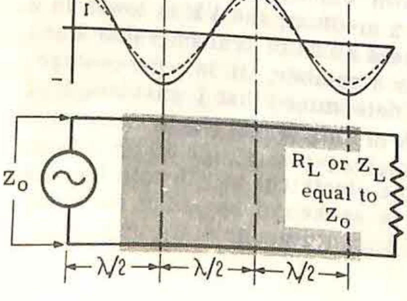
the line behaves as if a constant-amplitude voltage was applied to it.

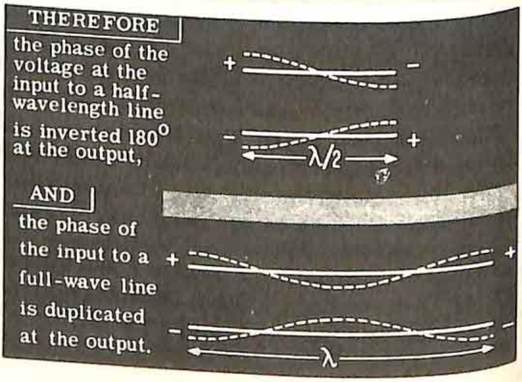


When an electromagnetic wave representative of energy between zero and maximum values advances along a transmission line terminated in a resistance equal to its Z_O, each point along the line from input to load is subject to like levels of energy from zero to maximum. Since this energy is the result of the application of a cyclic variation between zero and maximum of the input voltage, every point along the line is subject to voltage (and current) values between zero and maximum. Whether the line is long or short, no point will show any fixed value of voltage (or current) different from any other. In other words, there will be no points of maximum voltage or current (loops), or points of zero voltage or current (nodes), or any values in between. The line is flat.

Regardless of what may be the instantaneous polarity of the voltage (and current) at any point along the line, at a distance of 1 wavelength (λ) from this point, the polarity or phase is repeated. At a distance of a 1/2 λ however, the polarity or the phase are inverted. This is an important property of the 1/2-λ or full λ terminated line. A 1/2-λ line or odd multiple thereof is a polarity or a phase changer, while two 1/2-λ lines or even multiples of a 1/2-λ line become a polarity or phase repeater.

The Phase of Voltage and Current Changes Every Half-Wavelength





THEREFORE

the phase of the voltage at the input to a half-wavelength line is inverted 180° at the output,

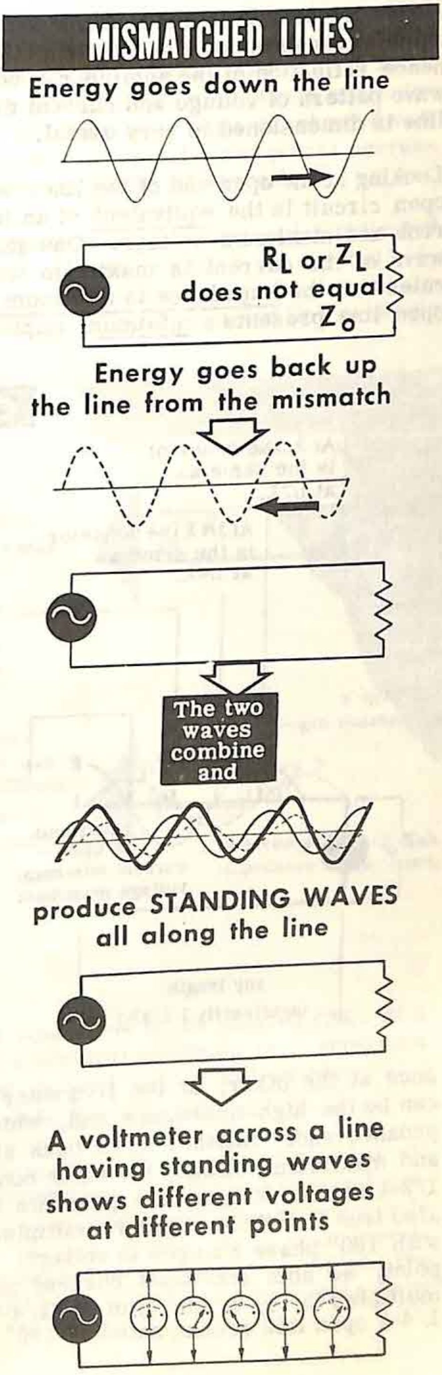
AND

the phase of the input to a full-wave line is duplicated at the output.

Transmission Line Not Terminated in Characteristic Impedance

It is conceivable that for any one of many possible reasons a transmission line may be terminated in a resistance not equal to its Z_o. If the difference in the ohmic values of the two is not too great, say 10 to 25%, it can be ignored in most instances. But if the difference is substantial, say 2 to 1, a new and important set of voltage and current conditions are created. Such a relationship between the ohmic values of the Z_o and the load is called an impedance mismatch. The greater the difference in the line and load impedances, the greater the mismatch.

Energy sent down the line toward the load finally reaches it, but is only partially absorbed. That portion not absorbed is reflected from the load, and travels back up the line to the generator. All the while energy is leaving the generator and advancing toward the load. So we have current and voltage traveling in two directions simultaneously in the line. Let us concern ourselves with only voltage, although reflection of current also occurs. The forward and reflected voltage waves combine and produce resultant sum voltage waves known as standing voltage waves. This means fixed points of maximum and zero voltage along the line. The ratio of maximum to minimum voltage is the standing wave ratio (SWR). The useful energy absorbed by the load is the difference between the forward energy and the reflected energy. Hence, the greater the mismatch the less energy sent down the line becomes useful energy. When a transmission line is used to deliver electrical energy from one point to the other, correct matching of the load impedance to the transmission line impedance is vital. A badly mismatched line makes it difficult to properly "dip" the final amplifier in a transmitter.

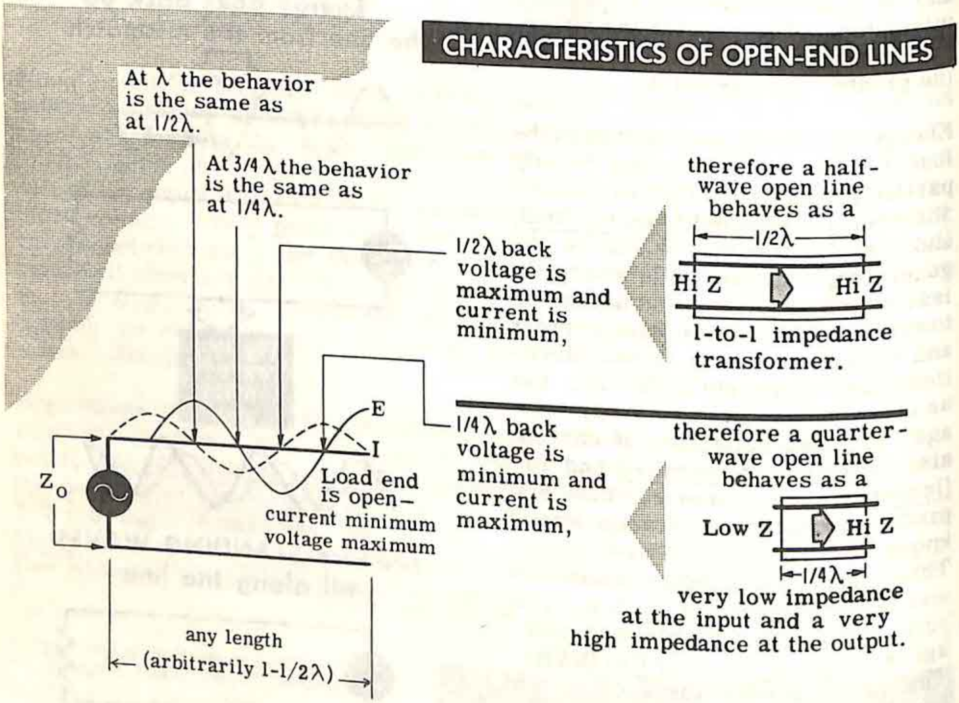

MISMATCHED LINES
Energy goes down the line
R_L or Z_L does not equal Z_o
Energy goes back up the line from the mismatch
The two waves combine and
produce STANDING WAVES all along the line
A voltmeter across a line having standing waves shows different voltages at different points

Resonant Transmission Lines (Open Circuited)

A resonant transmission line has standing waves of voltage and current. Imagine a transmission line open circuited at the load end. A mismatch exists, hence reflection of the applied r-f voltage and current occurs. The standing wave pattern of voltage and current distribution at the frequency for which the line is dimensioned is very useful.

Looking at the open end of the line, we say that the electrical condition of the open circuit is the equivalent of an infinite impedance; hence minimum current and maximum voltage. One quarter λ back from this point the standing wave of the current is maximum while the voltage is minimum. This indicates that the impedance is minimum, or a short-circuit exists. So, a 1/4-λ open line presents a minimum impedance at one end and a maximum impedance at the other, at the frequency for which the line is 1/4 λ. Either end can be the high-impedance end, which would make the other end the low-impedance end. Another 1/4 λ back along the line we note minimum current and maximum voltage; the same conditions as at the open load end. Thus, a 1/2-λ section of open line presents a high impedance at both ends. This is also true for whole number multiples (2, 3, 4, etc.,) of the 1/2-λ open line with 180° phase changes in voltage. Moving back another 1/4 λ to the 3/4 λ point, we note maximum current and minimum voltage again. Thus, odd multiples (3, 5, 7, etc.,) of the 1/4-λ open line duplicate the conditions of the 1/4-λ open line accompanied by 180° phase changes in the current.

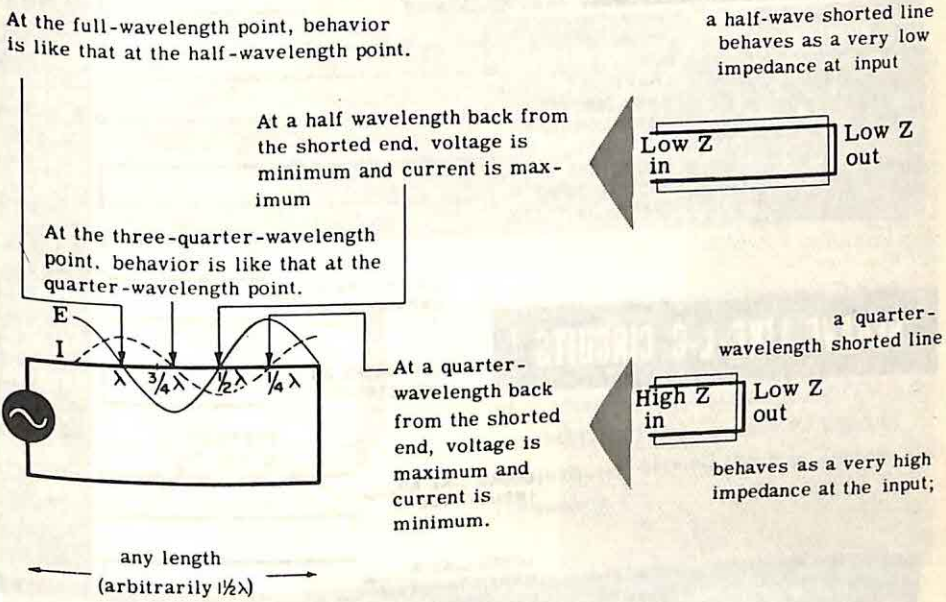
CHARACTERISTICS OF OPEN-END LINES


At λ the behavior is the same as at 1/2λ.
At 3/4 λ the behavior is the same as at 1/4λ.
1/2λ back voltage is maximum and current is minimum,
therefore a half-wave open line behaves as a
1/2λ
Hi Z
Hi Z
1-to-1 impedance transformer.
E
I
Z0
Load end is open— current minimum voltage maximum
1/4λ back voltage is minimum and current is maximum,
therefore a quarter-wave open line behaves as a
Low Z
Hi Z
1/4λ
very low impedance at the input and a very high impedance at the output.
any length (arbitrarily 1-1/2λ)

Resonant Transmission Lines (Short-Circuited)

Imagine another extreme case of mismatch – the shorted transmission line. An r-f voltage is applied and reflection occurs at the point of mismatch. Standing waves of current and voltage appear on the line. The current at the shorted end is maximum while the voltage is minimum, a condition which develops when the impedance is minimum. Working back from the shorted end, we note changing minimum and maximum impedance values at points corresponding to $1/4\,\lambda$, $1/2\,\lambda$, $3/4\,\lambda$, and λ at the frequency of operation.

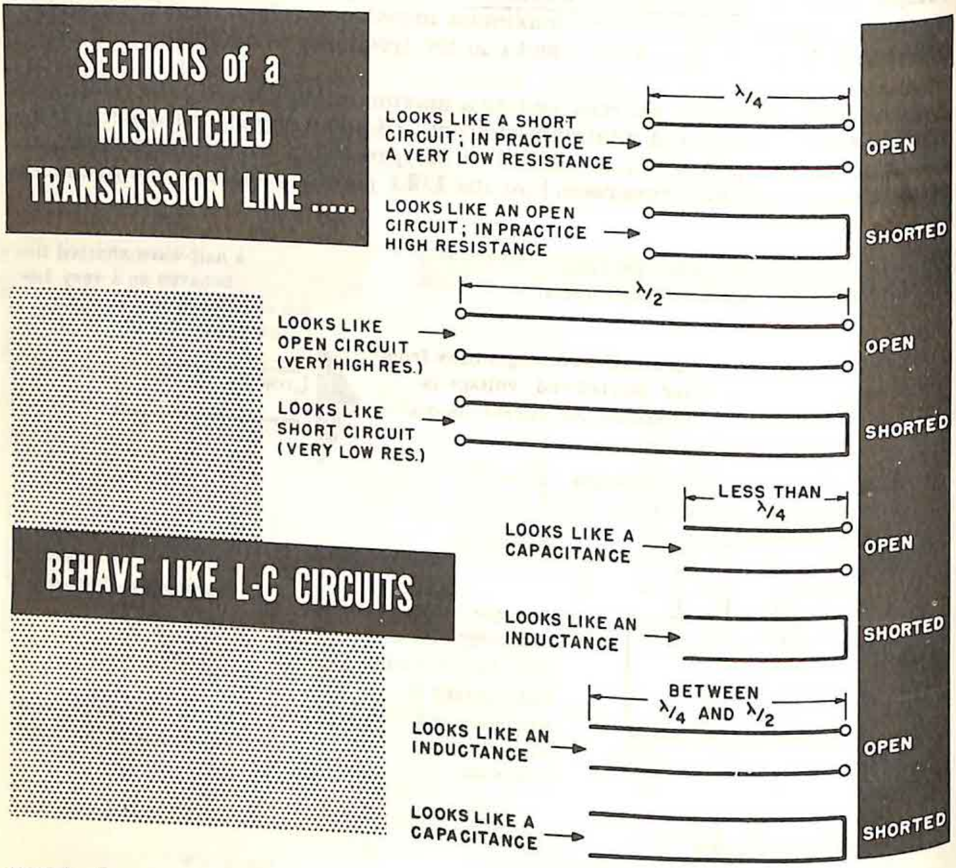
A $1/4\,\lambda$ back from the shorted end is a maximum impedance point indicated by maximum voltage and minimum current. (If you compare the shorted $1/4$-λ line with the open $1/4\,\lambda$ discussed on the preceding page, the impedance conditions are exactly reversed.) At the $1/2\,\lambda$ point the shorted line presents minimum impedance, a duplicate of the conditions at the shorted end. At a point $3/4\,\lambda$ back from the shorted end the electrical condition is a repetition of that which exists $1/4\,\lambda$ back from the shorted end. A full wavelength (λ) back, the impedance again is minimum, as at the $1/2\,\lambda$ point.


At the full-wavelength point, behavior is like that at the half-wavelength point.
At a half wavelength back from the shorted end, voltage is minimum and current is maximum
At the three-quarter-wavelength point, behavior is like that at the quarter-wavelength point.
E
I
λ
3/4 λ
1/2 λ
1/4 λ
At a quarter-wavelength back from the shorted end, voltage is maximum and current is minimum.
any length (arbitrarily 1½λ)
a half-wave shorted line behaves as a very low impedance at input
Low Z in
Low Z out
a quarter-wavelength shorted line
High Z in
Low Z out
behaves as a very high impedance at the input;

Summarizing the electrical conditions described above, we can say that odd multiples (3, 5, 7, etc.,) of the $1/4$-λ shorted line repeat the electrical conditions encountered at the $1/4\,\lambda$ point, accompanied by 180° phase changes in the voltage. Also, shorted transmission lines containing whole number multiples (2, 3, 4, 5, etc.,) of $1/2\,\lambda$ at the operating frequency duplicate the electrical conditions encountered in the $1/2$-λ shorted line, accompanied by 180° phase changes in the current.

Properties of Transmission-Line Sections

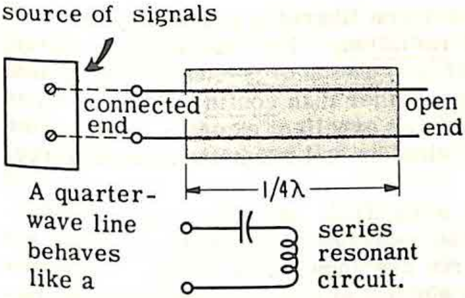
Although the main purpose of a transmission line is to deliver energy from one place to another, sections of an r-f transmission line can, under proper conditions, be used to simulate tuned circuits, circuit elements C and L, phase inverters, impedance transformers, and other similar devices. A tuned circuit displays certain forms of behavior at and around the frequency to which it is tuned; so will a resonant transmission-line section when the physical length of the section corresponds to the desired part of an electrical wavelength allowing for the velocity of propagation of the line. The following equations are useful for dimensioning r-f transmission lines:


SECTIONS of a MISMATCHED TRANSMISSION LINE .....
BEHAVE LIKE L-C CIRCUITS
λ/4
LOOKS LIKE A SHORT CIRCUIT; IN PRACTICE A VERY LOW RESISTANCE
OPEN
LOOKS LIKE AN OPEN CIRCUIT; IN PRACTICE HIGH RESISTANCE
SHORTED
λ/2
LOOKS LIKE OPEN CIRCUIT (VERY HIGH RES.)
OPEN
LOOKS LIKE SHORT CIRCUIT (VERY LOW RES.)
SHORTED
LESS THAN λ/4
LOOKS LIKE A CAPACITANCE
OPEN
LOOKS LIKE AN INDUCTANCE
SHORTED
BETWEEN λ/4 AND λ/2
LOOKS LIKE AN INDUCTANCE
OPEN
LOOKS LIKE A CAPACITANCE
SHORTED

$$\underset{\text{(in inches)}}{1/2\,\lambda} = \frac{5904 \times VP}{f\ (\text{MHz})} \qquad \underset{\text{(in inches)}}{1/4\,\lambda} = \frac{2952 \times VP}{f\ (\text{MHz})} \qquad \underset{\text{(in inches)}}{1/8\,\lambda} = \frac{1476 \times VP}{f\ (\text{MHz})}$$

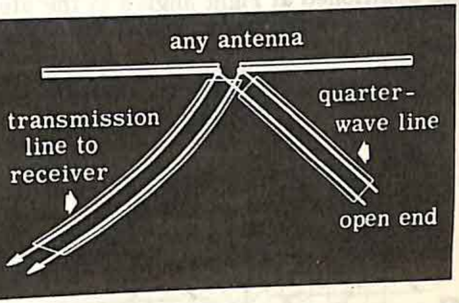
The action attributed to the section of the line takes place at the "input" end. This is the end opposite to where the line is shorted or open circuited. The device connected to the input end of the line "sees" the electrical condition.

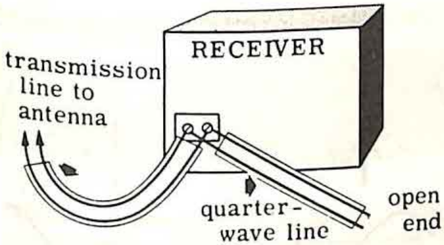
Typical Applications of Transmission-Line Sections



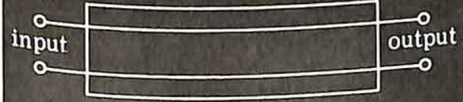
If a quarter-wavelength open line is connected across any source of signals, the source will "see" a very low impedance at the frequency for which the line was dimensioned.

A quarter-wave open line connected to an antenna will "short circuit" the antenna over a narrow band of frequencies around the frequency for which the line was dimensioned.

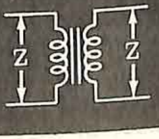




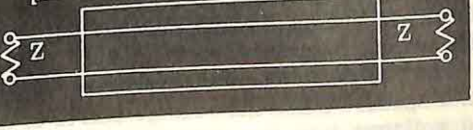
A quarter-wave open line cut for an interfering signal frequency and connected to the antenna terminals of a receiver will act as a short circuit (trap) over a narrow band of frequencies around the interfering frequency.



A half-wave open line acts as a 1-to-1 impedance transformer,



and a half-wave line terminated in a resistance or impedance Z will display the same impedance at the input, accompanied by a 180° phase inversion.

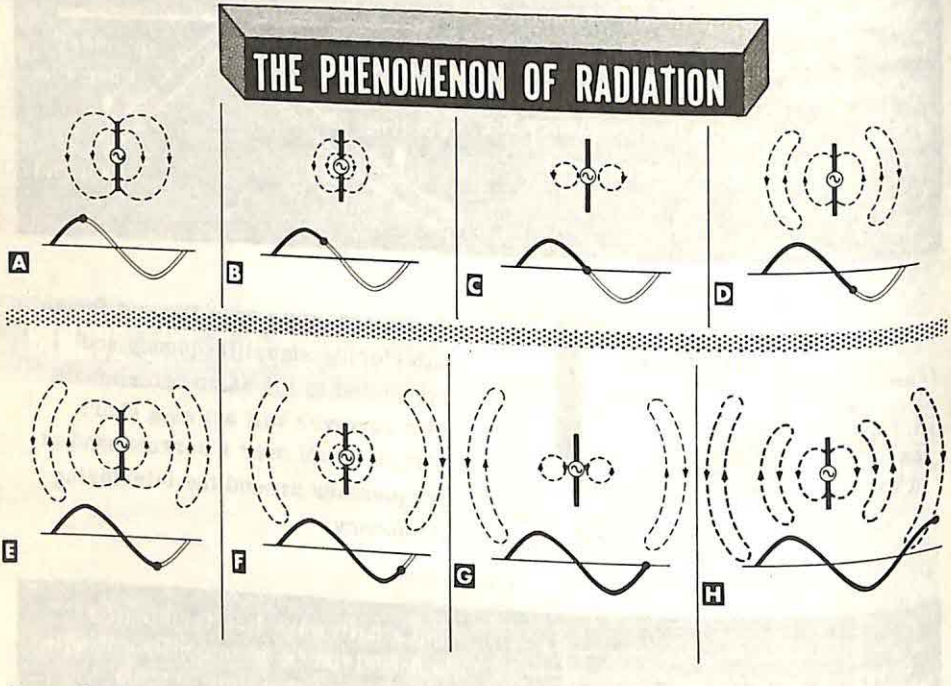


A few broad interpretations of the action of transmission-line sections are shown above. There are, of course, many others, several of which appear in the antenna section in this volume.

Radiation

The mechanism whereby a transmitting antenna liberates r-f energy delivered to it from a transmitter, is called radiation. For radiation to occur, changing current must flow in the antenna. The energy-converting system (antenna) must have capacitance with open rather than confined electric lines of force. The coaxial transmission line is an excellent example of a carrier of electromagnetic energy with confined electric and magnetic lines of force.

Although the action shown is very much simplified, and related to a particular type of antenna known as a dipole, the sequence of action is the same for all types. Only the electric loops of force are shown as a matter of convenience. Magnetic loops of force are also generated simultaneously, these being positioned at right angles to the electric loops of force. Lines of electric force having one direction of action build outward during the rise in voltage in an alternation, then tend to collapse back into the antenna when the voltage falls, but they cannot do so completely before the applied voltage changes its direction and generates new electric lines of force of a different direction. These too, expand outward, and in so doing push some of the previously collapsing electric lines of force away from the antenna, propagating them out into space. When the voltage starts to decrease, the new electric lines tend to collapse into the antenna, but cannot do so completely before the new cycle of voltage begins, hence these also are propagated into space. Thus the energy corresponding to the current and voltage fed to the antenna moves out into space as inseparably associated electric and magnetic loops of force.

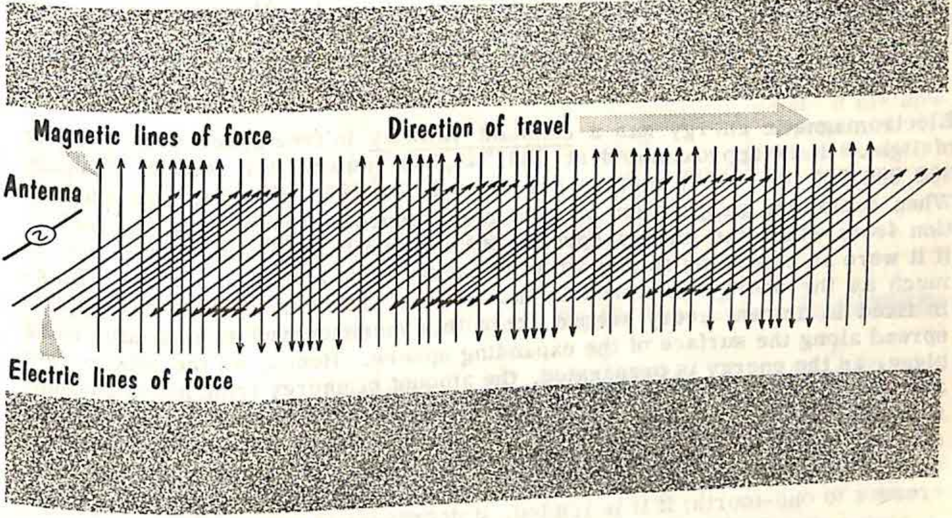

THE PHENOMENON OF RADIATION

Electric and Magnetic Fields in Free Space

The electromagnetic wave or radio wave radiated into free space consists of inseparably associated loops of electric and magnetic forces. Where they exist is called an electromagnetic field.

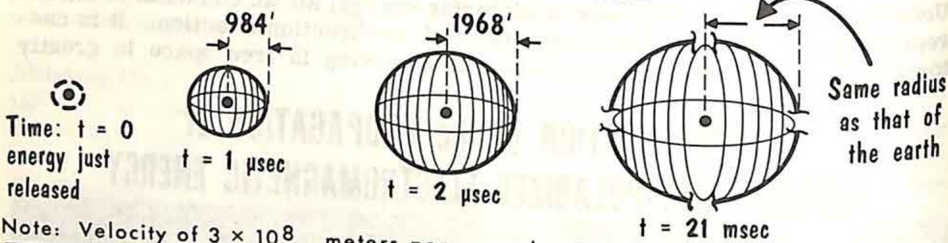
Unfortunately, there is no way of picturing energy; all we can do is to show a representation of where the energy is, and its direction of action. It is customary to show the electromagnetic field moving in free space in greatly simplified fashion by imagining that an observer in space "sees" tiny segments of the moving electric and magnetic loops of force passing by him. They appear as straight lines positioned at right angles to each other. The plane of the electric lines of force relative to the horizontal surface of the earth indicates the polarization of the radiation. In the illustration, the radiation is horizontally polarized, in which case the magnetic lines of force are perpendicular to the earth. Horizontally polarized waves are radiated by horizontally positioned antennas. In vertical polarization, the vertically polarized wave has its electric lines of force perpendicular to the earth's surface, and its magnetic lines of force parallel to the earth's surface. It is radiated by antennas which are similarly positioned. The changes in the direction of action of the lines of force of the field correspond to the changes in polarity of the driving voltage and current in the antenna which radiated the energy. Of greatest significance in the presentation of the electromagnetic field moving in free space is the fact that the directions of the electric and magnetic field lines of force are mutually perpendicular (differ by 90°) in space, but are in phase in time (both pass through maximum and zero together). Both are at right angles to the direction of advance of the energy.

REPRESENTATION of the PROPAGATION of HORIZONTALLY-POLARIZED ELECTROMAGNETIC ENERGY



The Free-Space Wave (Velocity, Frequency, and Wavelength)

The RADIO WAVE of a PULSE leaves a POINT SOURCE as an EXPANDING SPHERE of ENERGY — with the energy uniformly distributed ALONG the SURFACE of the SPHERE



Note: Velocity of 3×10^8 meters per second = 984 feet per µsec

Electromagnetic energy has a constant velocity in free space – the velocity of light. It is approximated at 299,744,000 meters per second, roughly 300,000,000 (3×10^8) meters per second, or 186,000 miles per second. When explaining propagation we assume a theoretical point source of radiation from which the energy spreads out uniformily in all directions, just as if it were an expanding sphere with the energy lying along the surface. Inasmuch as the energy delivered to the antenna and from the antenna to space is fixed in amount every second, only this much energy is available to be spread along the surface of the expanding sphere. Hence, as the sphere gets bigger as the energy is propagated, the amount of energy lying along any unit area of the sphere, decreases. Conforming with the geometric law that the surface area of a sphere increases as the square of its radius, the signal strength at any sampling point decreases inversely as the square of the distance to the transmitter. If the distance is doubled the signal strength decreases to one-fourth; if it is tripled, it decreases to one-ninth.

The frequency of the radiated wave is determined by the frequency of the voltages and currents applied to the radiating antenna. Concerning the electrical wavelength of the signal in free space, the term has exactly the same meaning as for the electromagnetic wave moving through a transmission line, with one difference. This is that the velocity of propagation of free space is 1, whereas for all other media it is some fraction of 1.

The Relationship Between VELOCITY (V), FREQUENCY (f), and WAVELENGTH (λ)

$$V \text{ (meter/second)} = f \text{ (Hz)} \times \lambda \text{ (meters)}$$

$$f \text{ (Hz)} = \frac{\text{velocity (meter/second)}}{\lambda \text{ (meters)}}$$

$$\lambda \text{ (meters)} = \frac{\text{velocity (meter/second)}}{f \text{ (Hz)}}$$

Example: A 20-MHz signal in free space

$$V \text{ (meter/second)} = 20{,}000{,}000 \times 15 = 300{,}000{,}000 \text{ meter/second}$$

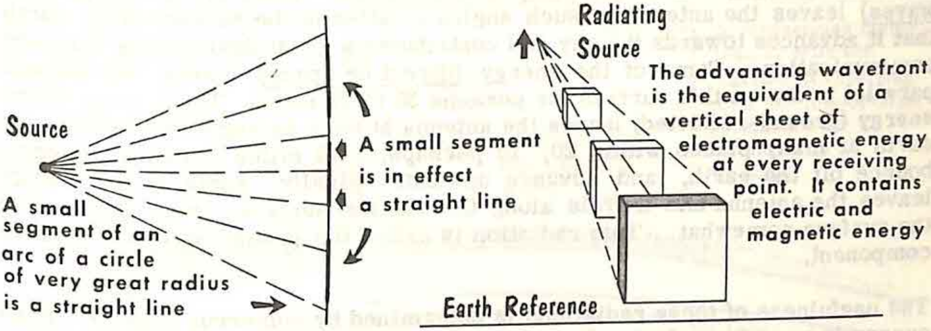
$$f \text{ (hertz)} = \frac{300{,}000{,}000}{15} = 20{,}000{,}000 \text{ Hz}$$

$$\lambda \text{ (meters)} = \frac{300{,}000{,}000}{20{,}000{,}000} = 15 \text{ meters}$$

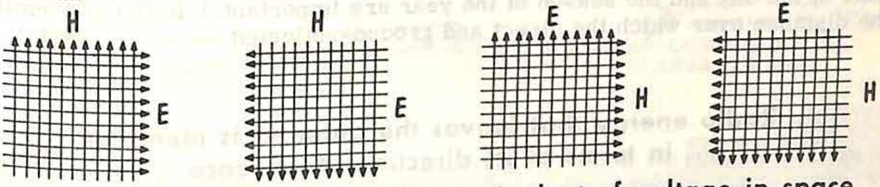
The Wavefront

Although we have spoken of spherical propagation of electromagnetic waves, an observer located in space (or at a receiving antenna) would "see" the radio wave approaching as a transverse plane surface or sheet of radio energy perpendicular to the direction of advance. We call the arriving sheet of energy the wavefront. Signal energy arriving at any receiving point arrives there as a wavefront. The wavefront is considered a plane rather than a curved surface because any tiny segment of a circle or sphere of great radius is for all intents and purposes a straight line or plane.

A RADIO WAVE APPROACHES as a SHEET of ENERGY


Source
A small segment of an arc of a circle of very great radius is a straight line
A small segment is in effect a straight line
Radiating Source
The advancing wavefront is the equivalent of a vertical sheet of electromagnetic energy at every receiving point. It contains electric and magnetic energy
Earth Reference

The Wavefront Consists of Electric and Magnetic Lines of Force



The electric lines of force are the equivalent of voltage in space

If we could see the makeup of the wavefront, it would consist of electric and magnetic lines of force (E and H lines) at right angles to each other. If at one instant the E lines pointed to the right, the H lines would point upward; if the E lines pointed to the left, the H lines would point downward. Polarization of the radiated energy is indicated by the plane of the E lines in the wavefront; horizontal E lines indicate horizontal polarization, whereas vertical E lines indicate vertical polarization. In either case the E lines are the equivalent of voltage in space, which if given the opportunity to act on an object lying in their path will induce a difference of potential (a voltage) in the object. Metallic objects (antennas) are subject to the maximum flow of current because of the voltage induced in the antenna. Horizontally positioned antennas are subject to the greatest difference of potential by horizontally polarized E lines, vertical antennas by vertical E lines in the wavefront.

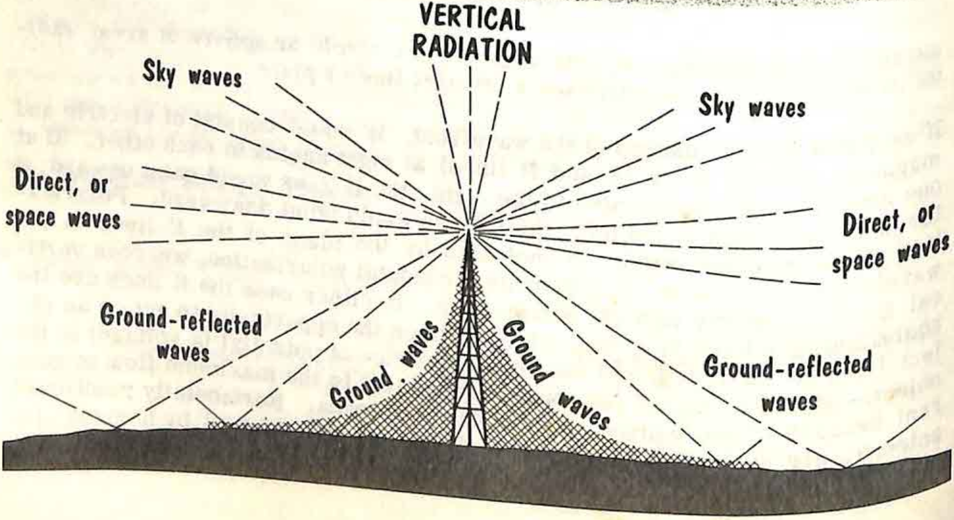
Practical Wave Propagation

Although radio propagation takes place in all directions from a theoretical antenna, the distribution of radiated energy from the practical antenna is not always uniform in all directions. Radio energy leaves the practical antenna in a number of significant directions which greatly influence the ability to communicate by this means. In showing the radiation we use the ray technique; actually the radiated energy fills in the spaces between the rays.

Some of the radiated energy is directed upward from the antenna. This is vertical radiation, and is generally of limited use. Some of the energy (sky waves) leaves the antenna at such angles relative to the surface of the earth that it advances towards the sky and contributes a great deal to long distance communication. Some of the energy (direct or space) leaves the antenna parallel to the earth's surface for perhaps 30 to 75 miles. Then, some of the energy (ground-reflected) leaves the antenna at such an angle as to strike the earth at many places within 20, to perhaps, 75 miles from the antenna, bounce off the earth, and advance upward. Finally, some of the energy leaves the antenna and travels along the earth's surface – even penetrating the surface somewhat. This radiation is called the ground wave or surface component.

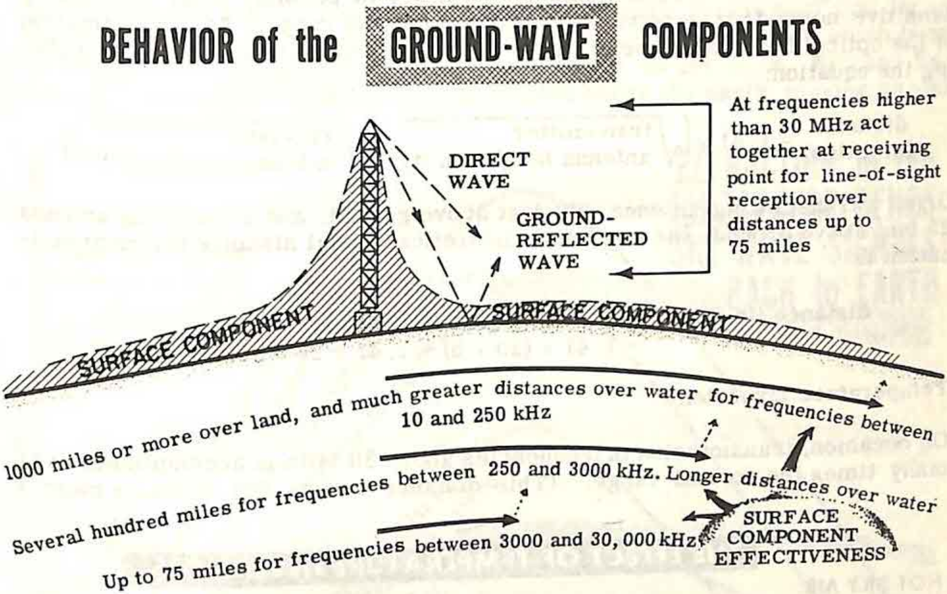
The usefulness of these radiations is determined by numerous factors. Frequency is very important. It determines, for example, the extent to which the ground wave is useful; it also determines which of the radiations directed towards the sky will return to earth, and which will be lost in space. (The time of the day and the season of the year are important.) It also determines the distance over which the direct and ground-reflected waves are useful.

Radio energy that leaves the antenna is identified in terms of its direction of advance



Ground, Ground-Reflected, and Direct Waves

It is generally felt that the ground wave embraces all radiations other than the sky waves and vertical radiation. Taking this approach, ground-wave radiation consists of three components: the surface component, which moves along the surface of the earth with the bottom edge of its wavefront in contact with the surface of the earth, in which it induces minute earth currents; poor conductivity, dry, sandy soil tends to attenuate the earth currents thus limiting the range of communication. Moist soil or salt water are high-conductivity paths which aid propagation, and therefore extend greatly the distance that can be spanned by this radiation. The most useful frequencies are those up to about 3 MHz, although the surface component is effective over shorter distances at frequencies up to 30 MHz.


BEHAVIOR of the GROUND-WAVE COMPONENTS
DIRECT WAVE
GROUND-REFLECTED WAVE
At frequencies higher than 30 MHz act together at receiving point for line-of-sight reception over distances up to 75 miles
SURFACE COMPONENT
SURFACE COMPONENT
1000 miles or more over land, and much greater distances over water for frequencies between 10 and 250 kHz
Several hundred miles for frequencies between 250 and 3000 kHz. Longer distances over water
Up to 75 miles for frequencies between 3000 and 30,000 kHz
SURFACE COMPONENT EFFECTIVENESS

When the frequency of radiation is higher than 30 MHz, and the distance to be spanned is within about 75 miles, the signal reaching the receiving antenna is a combination of the direct and the ground-reflected waves. This is called line-of-sight reception because the transmitting and receiving antennas can usually "see" each other. Two phenomena are significant in line-of-sight reception. The direct and ground-reflected waves leave the transmitting antenna with the same signal phase but travel different paths to the receiving antenna. These paths may be of different length. Because the ground-reflected signal suffers a 180° phase reversal at the point of reflection, it is conceivable that the two signals may aid or oppose each other in the receiving antenna. The resultant signal may be stronger or weaker than the direct-path signal alone. Varying the height of the receiving antenna can improve a weakened signal situation.

Line-of-Sight Propagation: Temperature Inversion

The effectiveness of line-of-sight propagation depends on the relative heights of the transmitting and receiving antennas, that is, the ability of the two devices to "see" each other. The amount of power radiated by the transmitting antenna will have a great influence on the distance covered. Transmitters rated at 1 or 2 watts or less will seldom span these distances. Sometimes, they will be effective only over a mile, or possibly less. Extremely sensitive noise-free receivers greatly extend the range. An approximation of the optical horizon or useful range of transmission can be made by applying the equation:

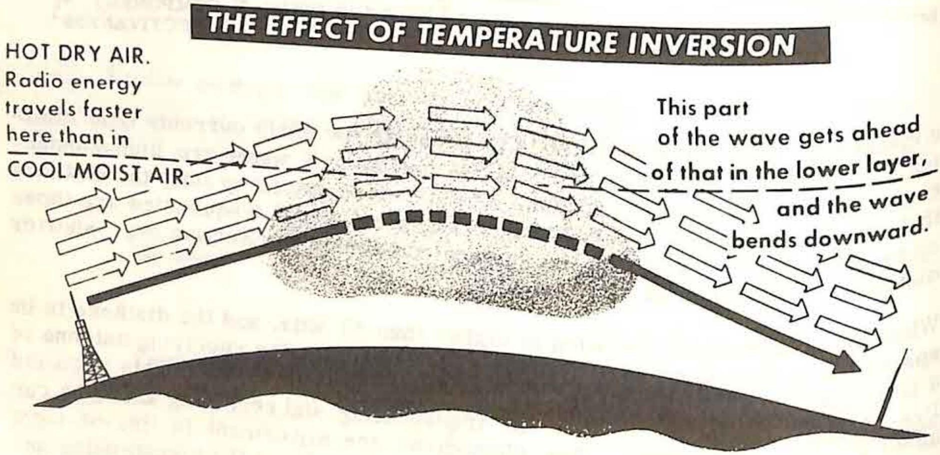
$$\begin{matrix}\text{distance}\\\text{(in miles)}\end{matrix} = 1.41 \times \left(\sqrt{\begin{matrix}\text{transmitter}\\\text{antenna height (in ft)}\end{matrix}} + \sqrt{\begin{matrix}\text{receiver}\\\text{antenna height (in ft)}\end{matrix}}\right)$$

Given a transmitting antenna 400 feet above ground, and a receiving antenna 25 feet above ground, the maximum theoretical useful distance for communication is

$$\begin{aligned}\text{distance (in miles)} &= 1.41 \times \left(\sqrt{400} + \sqrt{25}\right)\\ &= 1.41 \times (20 + 5) = 1.41 \times 25 = 35.25 \text{ miles}\end{aligned}$$

Temperature Inversion

On occasion, transmission of frequencies above 30 MHz is accomplished over many times the normal range. (This distance may be 500 miles or more.)



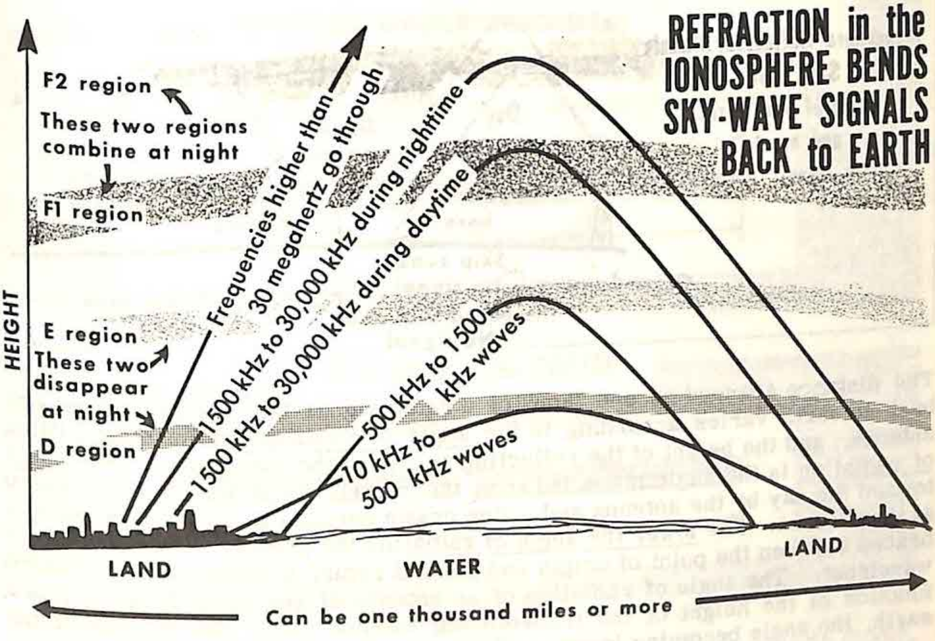
THE EFFECT OF TEMPERATURE INVERSION

HOT DRY AIR.
Radio energy travels faster here than in
COOL MOIST AIR.
This part of the wave gets ahead of that in the lower layer,
and the wave bends downward.

The relatively long distance transmission is attributable to a phenomenon known as temperature inversion. At certain times during the year, usually Spring and Fall, sometimes in the summer, layers of hot, dry air may be at higher elevations above the earth than cool, moist air. Radiation that normally would pass over antennas near the ground is bent back to earth, striking receiving antennas far beyond the optical horizon as seen from the transmitting antenna.

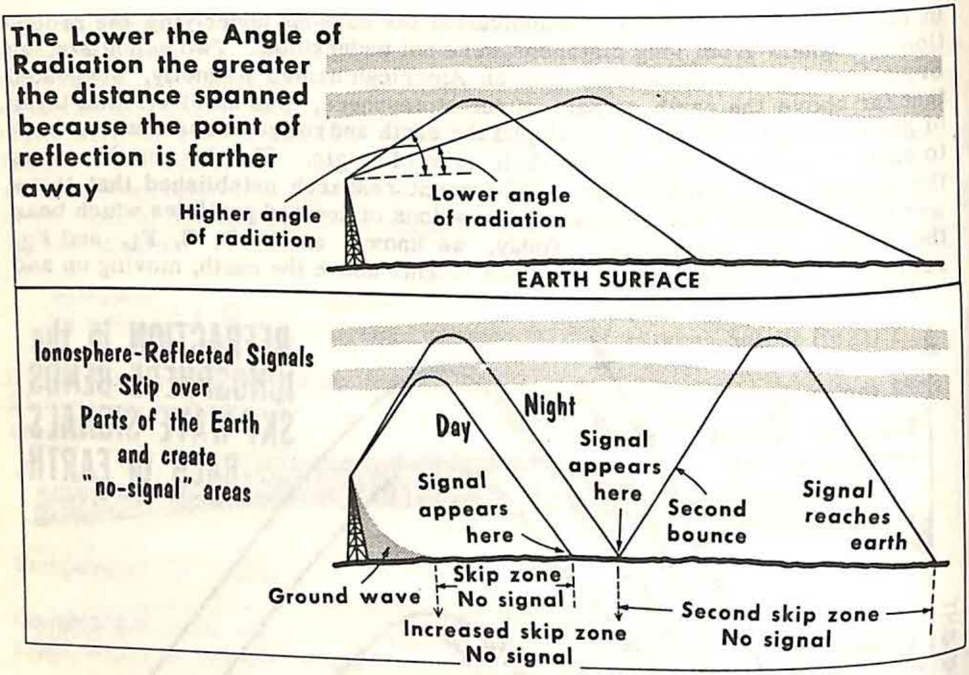
Sky-Wave Propagation (The Ionosphere)

In the early days of radio communication the reasons underlying the reception of signals from long distances were not understood. Two scientists, an Englishman named Heaviside, and an American named Kennelly, suggested that far above the earth as part of our atmosphere, was an electrified layer of gaseous particles which enveloped the earth and reflected radio waves back to earth at a long distance from their point of origin. This became known as the Kennelly-Heaviside layer. Subsequent research established that there was not one layer, but several deep regions of ionized particles which bear the single name ionosphere. Today, we know it as the D, E, F_1, and F_2, regions. The regions exist at various heights above the earth, moving up and down at different times of the day, week, month, and year. The F_1, and F_2 regions combine at night during winter and summer into a single F region, whereas the D and E regions apparently disappear at night.


REFRACTION in the IONOSPHERE BENDS SKY-WAVE SIGNALS BACK to EARTH
HEIGHT
F2 region
These two regions combine at night
Fl region
E region
These two disappear at night
D region
Frequencies higher than 30 megahertz go through
1500 kHz to 30,000 kHz during nighttime
1500 kHz to 30,000 kHz during daytime
500 kHz to 1500 kHz waves
10 kHz to 500 kHz waves
LAND
WATER
LAND
Can be one thousand miles or more

The ionized state is produced by bombardment of the upper regions of our atmosphere by gamma rays, ultraviolet rays, electrons, and other particles emitted by the sun, as well as cosmic rays from outer space. By virtue of the variation in density of the atmosphere at different heights above the earth, different degrees of ionization exist during the day and night, at different times of the year. The importance of the changing ionization and the changing height of the ionized regions above the earth is in the way in which they permit sky-wave radiations of certain frequencies which enter these regions to pass through them, while others are bent back (refracted) towards the earth. Sometimes we say that the energy is reflected back to earth.

Angle of Radiation and Skip Distance


The Lower the Angle of Radiation the greater the distance spanned because the point of reflection is farther away
Higher angle of radiation
Lower angle of radiation
EARTH SURFACE
Ionosphere-Reflected Signals Skip over Parts of the Earth and create "no-signal" areas
Day
Night
Signal appears here
Signal appears here
Second bounce
Signal reaches earth
Ground wave
Skip zone No signal
Increased skip zone No signal
Second skip zone No signal

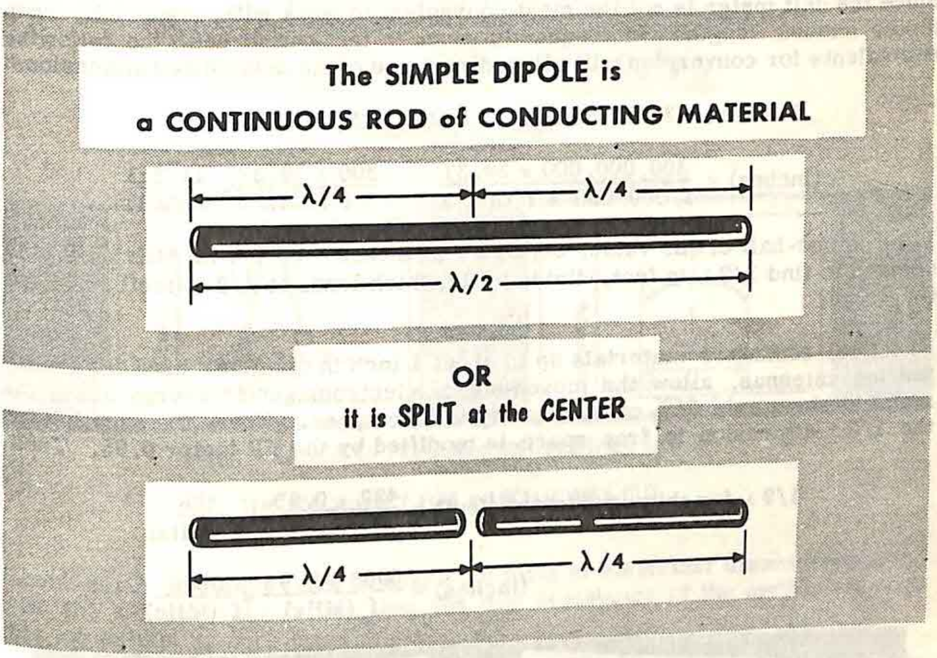
The distance spanned by one "hop" of a radio signal into the ionosphere and back to earth varies according to the angle of radiation of the transmitting antenna, and the height of the reflecting region in the ionosphere. The angle of radiation is the angle made between the center of the wavefront radiated toward the sky by the antenna and a line drawn parallel to the earth's surface at the antenna. The lower the angle of radiation the greater the distance embraced between the point of origin and point of return to earth of the reflected wavefront. The angle of radiation of an antenna of any given frequency is a function of the height of the transmitting antenna above the surface of the earth, the angle becoming lower as the antenna height is increased.

It is characteristic of ionosphere reflected waves that the point of nearest return to earth is at a greater distance from the transmitting antenna than the distance covered by ground-wave radiation. Thus, there is a silent or skip zone between where the surface ground-wave radiation becomes ineffective, and the reflected sky-wave signal is first detected. This skip distance may be many hundreds of miles or more. As the signal frequency is increased, skip distance is increased. Long-distance coverage is also accomplished by multiple hops of the radiated energy. After being reflected back to earth from the ionosphere the first time, the signal bounces off land or sea surface toward the sky, to return to the earth again at a much greater distance. Thus, a signal leaving New York City could reach Los Angeles on the first bounce; Hawaii on the second bounce and farther distances by additional reflections. All radiations reflected to earth again bounce off, but the energy may not always be sufficient to be detected at the second and third points of return.

The Fundamental Antenna

A transmitting antenna is a structure made of metal which liberates (radiates) radio-frequency current and voltage supplied to it as electromagnetic energy into space. A receiving antenna also is a structure made of metal which intercepts electromagnetic energy moving through space, and converts it into voltage and current of corresponding frequency.

The fundamental radio antenna is a metal rod or tubing which has a physical length approximately equal to one-half wavelength in free space at the frequency of operation. Such a structure is known as a half-wavelength dipole, which name is often abridged to half-wave dipole. It is also known as the Hertz antenna. Sometimes the half-wave dipole is called a half-wave doublet. Dipole and doublet mean the same thing as long as the electrical dimensions of the two are the same. A dipole antenna is defined as "a symmetrical antenna in which the two ends are at equal potential relative to the midpoint."


The SIMPLE DIPOLE is
a CONTINUOUS ROD of CONDUCTING MATERIAL
λ/4
λ/4
λ/2
OR
it is SPLIT at the CENTER
λ/4
λ/4

A half-wave dipole (or doublet) is usually positioned horizontally relative to the earth's surface, but, it can, if properly supported, be mounted vertically or obliquely. Another identity given the half-wave dipole is "zero-db gain antenna." This identification is useful only when some other structure used as an antenna affords certain advantages in the concentration of radiation, and is compared with the half-wave dipole. Such concentration of radiation is, as you shall see, the equivalent of having obtained more energy from the transmitter, without actually doing so.

The Half-Wavelength Dimension

The wavelength symbolized by the Greek letter (λ) called lambda, of any signal in free space is given by

$$\lambda\ (\text{meters}) = \frac{\text{velocity of propagation (meters per second)}}{\text{frequency of signal (hertz)}}$$

$$= \frac{300,000,000}{(\text{hertz})}$$

Since the unit meter is not the most convenient to work with, especially when dipole antenna lengths are frequently given in feet and inches, the following equivalents for conversion will allow direct use of the determined dimensions:

1 meter = 39.37 inches 1 MHz = 1,000,000 hertz

$$\lambda\ (\text{inches}) = \frac{300,000,000 \times 39.37}{1,000,000 \times f\ (\text{hertz})} \qquad \frac{300 \times 39.37}{f\ (\text{MHz})} = \frac{11,811}{f\ (\text{MHz})}$$

$1/2\ \lambda$ is one-half of this value, or, $1/2$ in inches = $5906/f$ (in MHz). If it is desired to find $1/2\ \lambda$ in feet, divide by 12, which leads to $1/2\ \lambda$ (feet) = $492/f$ (in mc).

Practical conductor materials up to about 1 inch in diameter used for transmitting antennas, allow the movement of electromagnetic energy along the metal at about only 95% of its velocity in free space. Thus, the equation for the $1/2\ \lambda$ dimension in free space is modified by the VP factor 0.95. Then,

$$1/2\ \lambda \text{ for thin conductors (feet)} = \frac{492 \times 0.95}{f\ (\text{MHz})} \quad \frac{468}{f\ (\text{MHz})}$$

$$(\text{inches}) = \frac{5906 \times 0.95}{f\ (\text{MHz})} = \frac{5609}{f\ (\text{MHz})}$$

FINDING WAVELENGTH

Frequency = 20 MHz

Wavelength = ?

$$\text{Wavelength (meters)} = \frac{300,000,000}{\text{Frequency (hertz)}}$$

$$= \frac{300,000,000}{20,000,000}$$

$$= 15 \text{ meters}$$

Wavelength = 15 meters

FINDING FREQUENCY

Wavelength = 15 meters

Frequency = ?

$$\text{Frequency (hertz)} = \frac{300,000,000}{\text{Wavelength (meters)}}$$

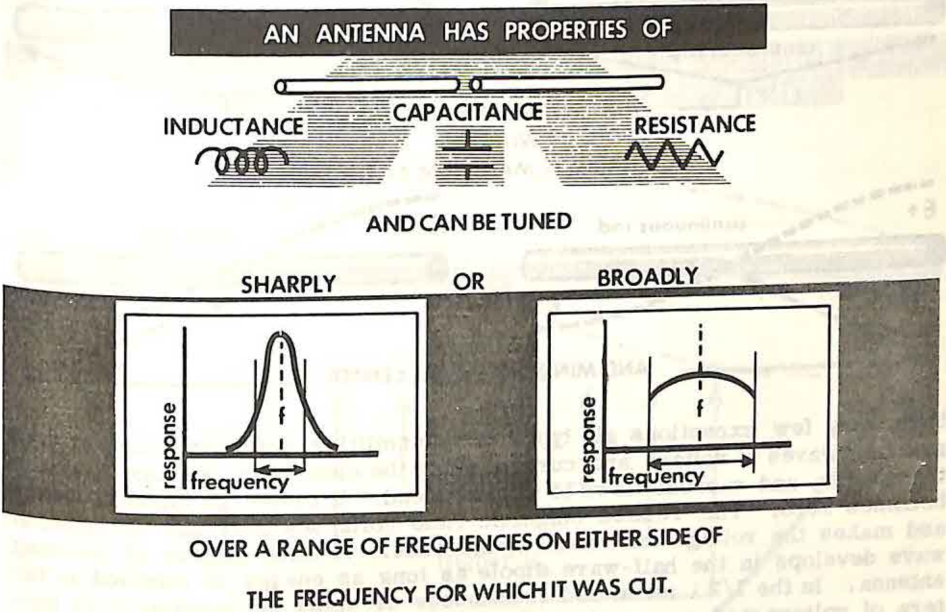
$$= \frac{300,000,000}{15}$$

$$= 20,000,000$$

Frequency = 20,000,000 hertz
= 20 MHz

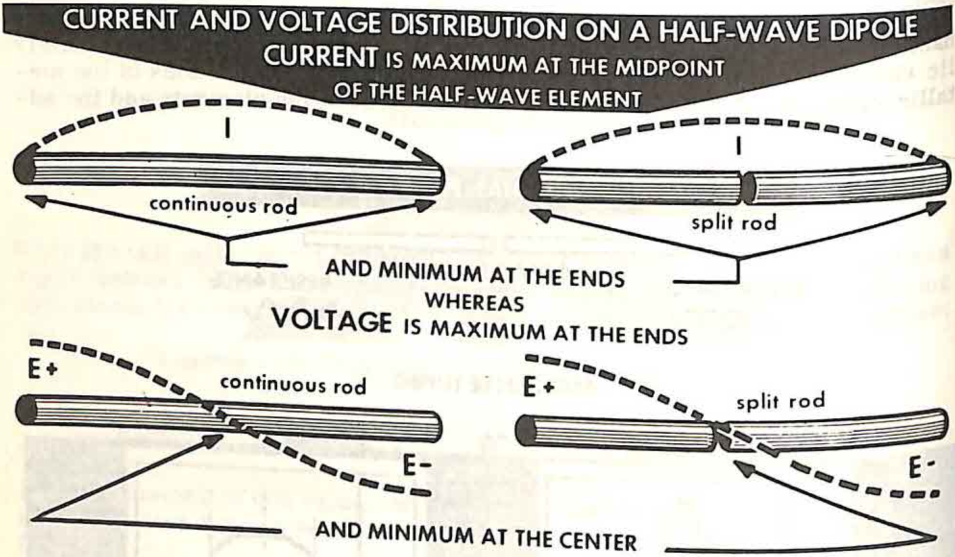
Resonance in the Half-Wave Dipole

Every half-wave dipole (continuous rod or split) is the equivalent of a resonant circuit. It has distributed L, C, and R. The L is present in the metallic elements when current flows. The C exists between portions of the metallic elements of the antenna, as well as between the elements and the adjacent earth (ground). The R takes the form of electrical losses associated with the r-f currents rather than the d-c resistance of the metal, although this too exists.


AN ANTENNA HAS PROPERTIES OF
INDUCTANCE
CAPACITANCE
RESISTANCE
AND CAN BE TUNED
SHARPLY
OR
BROADLY
response
frequency
f
response
frequency
f
OVER A RANGE OF FREQUENCIES ON EITHER SIDE OF
THE FREQUENCY FOR WHICH IT WAS CUT.

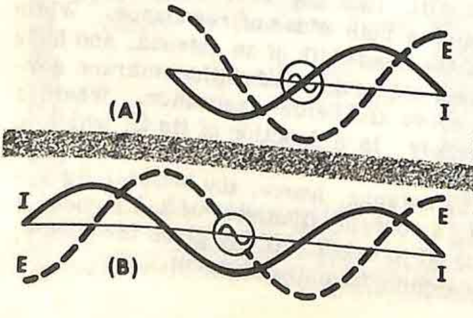
Like the conventional L-C circuit, a half-wave dipole antenna can be made resonant only to one frequency, the frequency for which it has been "cut." This frequency is determined by the L-C constants, principally by L, that is, the length of the antenna elements. To change the resonant frequency, the length of the elements is altered as needed. Although the half-wave dipole is dimensioned for a certain frequency it will, like any resonant L-C circuit, function over a narrow range of frequencies both sides of resonance. While it is impossible to set definite limits of the bandwidth of an antenna, and have it apply to every antenna, we can say that the usual bandwidths embrace several percent of the resonant frequency above and below resonance. Whether the antenna will "tune" broadly or sharply, is a function of its Q, which in turn is a function of the outside diameter of the antenna elements. The larger this diameter, the lower the Q of the antenna, hence, the broader its acceptance bandwidth. Equally important, an outside diameter of 2.5 inches or more can reduce the physical length equal to a 1/2 λ at any given frequency, by as much as 10% of that for a 0.5- or 1-inch diameter element.

Voltage and Current in the Half-Wave Dipole


CURRENT AND VOLTAGE DISTRIBUTION ON A HALF-WAVE DIPOLE
CURRENT IS MAXIMUM AT THE MIDPOINT
OF THE HALF-WAVE ELEMENT
I
continuous rod
I
split rod
AND MINIMUM AT THE ENDS
WHEREAS
VOLTAGE IS MAXIMUM AT THE ENDS
E+
continuous rod
E-
E+
split rod
E-
AND MINIMUM AT THE CENTER

With very few exceptions all types of transmitting antennas function with standing waves of voltage and current along the elements. Voltage is fed to the antenna and current flows to the open end. It cannot go further, hence becomes zero. The related magnetic field collapses back into the antenna and makes the voltage maximum at the ends. A fixed pattern of standing wave develops in the half-wave dipole as long as energy is supplied to the antenna. In the 1/2 λ metal rod (continuous or split) the standing wave pattern of voltage and current has the voltage maximum at the ends and minimum at the center. The current is maximum at the center and minimum at the ends.

The standing wave of voltage and current is not influenced by the orientation of the antenna; it can be physically positioned horizontally, vertically, or obliquely. Neither is the standing wave pattern influenced by the amount of energy supplied to the antenna; the pattern is the same for small and large amounts of power, and it is the same for small diameter or large diameter elements.



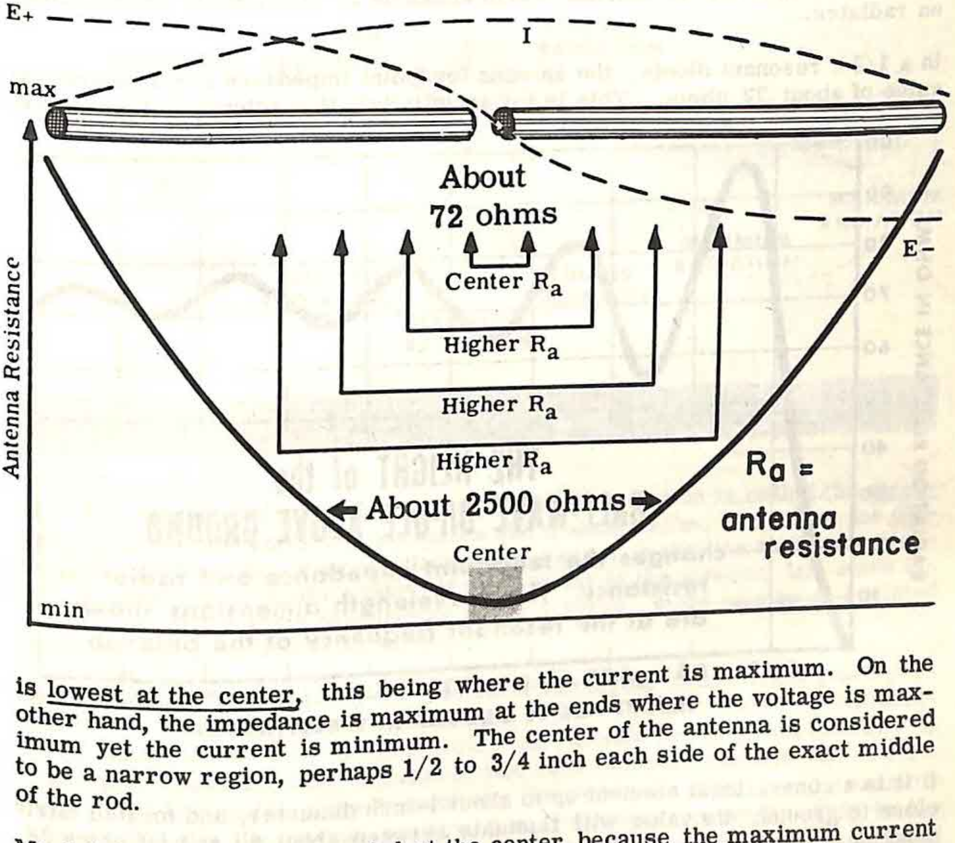
IN a WIRE ONE WAVELENGTH LONG (A) current I is minimum at the center, while voltage E is maximum

IN A WIRE THREE HALF-WAVELENGTHS LONG (B) the current I is maximum at the center while voltage E is minimum

Antenna Impedance

A characteristic of the standing waves of voltage and current on the half-wave dipole (or, on any antenna on which standing waves exist) is that the ratio between E and I, or E/I is not constant along the length of the antenna. The reason is that I and E do not change together. If we use the ratio E/I to express the impedance of the antenna, the impedance is not constant along the length of the element. Assuming a resonant half-wave dipole, the impedance is lowest at the center, this being where the current is maximum. On the other hand, the impedance is maximum at the ends where the voltage is maximum yet the current is minimum. The center of the antenna is considered to be a narrow region, perhaps 1/2 to 3/4 inch each side of the exact middle of the rod.

THE ANTENNA RESISTANCE OF A HALF-WAVE DIPOLE AT RESONANCE IS LOWEST AT THE CENTER AND INCREASES SYMMETRICALLY ON EACH SIDE OF THE CENTER.

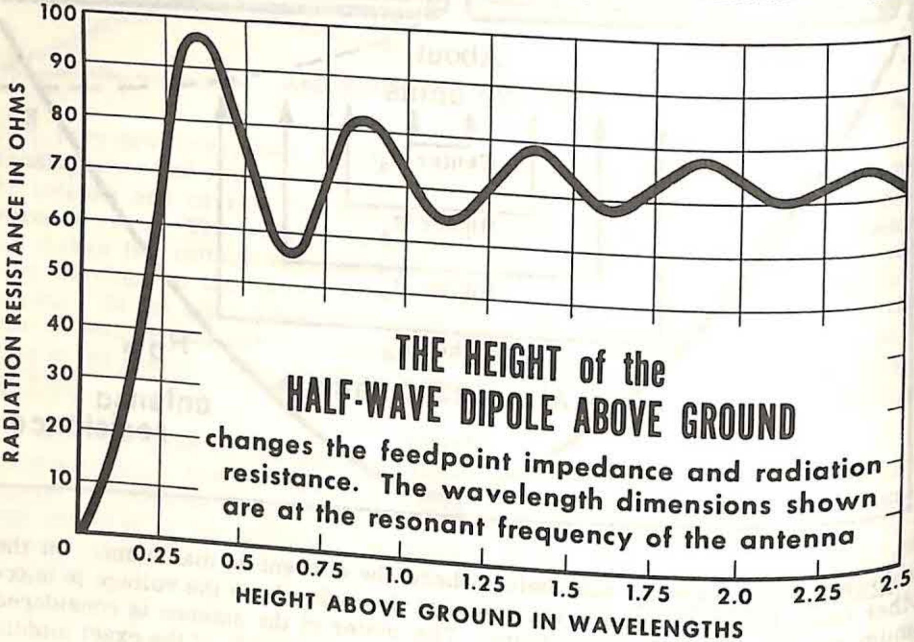


Most half-wave dipoles are fed at the center because the maximum current point is the minimum voltage point, and it is easier to produce transmission lines for low voltage than for high voltage. Also, when the half-wave dipole is resonant, the capacitive reactance and inductive reactance cancel each other, leaving resistance only as the net impedance. Under such conditions the antenna impedance is resistive between any two points equidistant from the center along the antenna length.

Antenna Input Impedance and Radiation Resistance

The desired electrical relationship between a transmitter and an antenna is when as much as possible of the power generated in the transmitter is delivered to the antenna. Similarly, it is desirable to deliver to the receiver the maximum possible amount of energy intercepted by the antenna. For this to happen, the "input" to the antenna must match the characteristic impedance of the transmission line, which in turn is assumed to match the output impedance of the transmitter. Thus, the important aspect of antenna impedance is the impedance at the point where the transmission line is connected. This point is called by several names, antenna input impedance, feedpoint impedance, and radiation resistance. Of these three names the first two are self-evident. Radiation resistance is defined as a fictitious resistance which when substituted for the antenna would consume as much power as the antenna radiates.

In a 1/2 λ resonant dipole, the antenna feedpoint impedance has a theoretical value of about 72 ohms. This is for an infinitely thin antenna in free space.



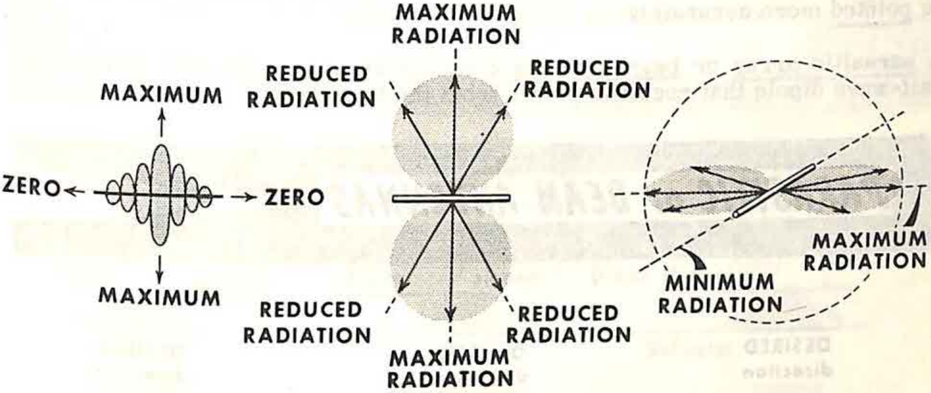
THE HEIGHT of the HALF-WAVE DIPOLE ABOVE GROUND changes the feedpoint impedance and radiation resistance. The wavelength dimensions shown are at the resonant frequency of the antenna

If it is a conventional element up to about 1-inch diameter, and located fairly close to ground, its value will fluctuate between about 60 and 90 ohms depending on the antenna height above ground. If the diameter of the antenna element is 2 or 3 inches, the feedpoint impedance can be as low as 35 ohms. While we say that the feedpoint impedance or the radiation resistance is purely resistive, this is true only when the wavelength of the dipole corresponds to the frequency of operation. Fortunately, however, there is enough latitude to permit the antenna to accept energy from the transmitter over a narrow band of frequencies each side of the resonant frequency.

Directivity of Resonant Half-Wave Dipole

While a point-source radiator located in space radiates equally in all directions, this is never true with practical antennas. All antennas radiate more energy in some directions than in others. The directions in which an antenna radiates best is the favorable direction for response as a receiving antenna. A pictorial representation of the pattern of radiation is called the directivity pattern, and applies to reception and transmission. The cause for directional radiation by a resonant half-wave antenna is that the radiation intensity is proportional to the square of the current in the antenna, but since the current is not the same everywhere in the antenna, more energy is radiated from certain parts than from others.

ALL RESONANT HALF-WAVE DIPOLES
radiate best and afford best signal pickup
broadside to the antenna element

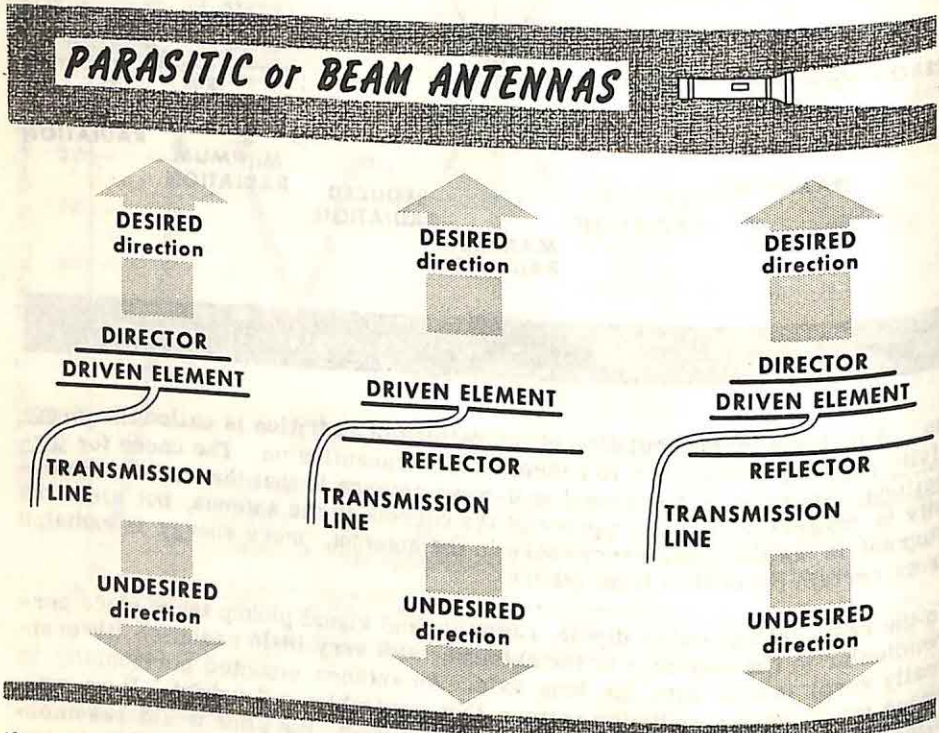


In the resonant half-wave dipole, radiation and signal pickup takes place perpendicular to the long axis of the antenna, with very little radiation (theoretically zero) in line with the long axis. An antenna mounted horizontally in space would have a radiation pattern that resembles a doughnut. If we cut a slice in the horizontal plane through the doughnut, the slice would resemble a figure 8, with the antenna positioned at the crossover point. This is the characteristic radiation and signal pickup pattern of a horizontally positioned resonant half-wave antenna. If the long axis pointed east-west, maximum radiation and signal pickup would be north and south, and vice-versa. It is standard practice to orient horizontally-positioned antennas so that an imaginary line drawn normal from the midpoint of the antenna element would point in the desired direction. The proximity of ground to the antenna affects the radiation pattern by changing the angle of radiation in the vertical plane.

Parasitic Arrays (Yagi Antennas)

The parasitic array is a way of using resonant half-wave dipoles to concentrate radiation in a desired direction and minimize radiation in undesired directions. This affords gain in the antenna. The reference is the half-wave resonant dipole previously identified as the zero db gain antenna. If an antenna design is said to afford a gain of 3 db, the result relative to radiated energy in a chosen direction is the same as if the zero db gain resonant half-wave dipole had been used with twice as much power obtained from the transmitter. (3 db = 2 time increase in power; 6 db = 4 time increase in power; 10 db = 10 time increase in power.) An antenna with gain tends to concentrate the radiated energy into a narrower beam, therefore the antenna must be pointed more accurately.

A parasitic array or beam antenna contains several elements: a resonant half-wave dipole that receives power from the transmitter, or which delivers the received power to the receiver, and is called the driven element; also, one or more continuous metal rods (the parasitic elements) which are parallel to the driven element at the same "line-of-sight" level. The rods are electrically coupled to, but not connected to, the driven element. The rod in front of the driven element is the director. Sometimes, two or more directors are used. The rod in back of the driven element is the reflector, of which only one is used. Frequently both director and reflector are used with the driven element in the same antenna.

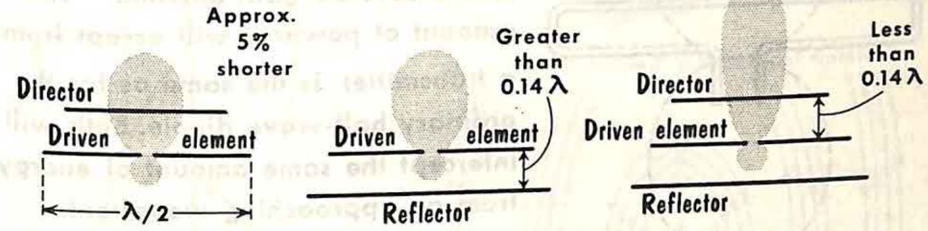

PARASITIC or BEAM ANTENNAS

Operation and Characteristics of the Parasitic Array

When treated in terms of transmission. energy is delivered to the driven element. It radiates energy towards the front and the rear. Some of this energy induces current in the parasitic element(s), which in turn reradiate virtually all the energy. By suitable dimensioning of the parasitic relative to the driven element, as well as the electrical distance between them, the electrical energy reradiated by the parasitic is "timed" to reinforce the current in the driven element. It also reinforces the radiation in front of the antenna, while tending to cancel the radiation towards the rear. The result is concentration of the radiation towards the front of the antenna i. e., towards the desired direction. When receiving, the parasitic element(s) and the driven element are acted upon by the approaching wavefront, but not at the exact moment because of the spacing between them. By suitable electrical timing (the spacing and the dimensions of the elements) energy received from the front of the antenna is reinforced in the driven element; energy arriving from the rear is effectively cancelled in the driven element.

PARASITIC ARRAYS RADIATE TOWARDS THE FRONT

with minimum radiation (and signal pickup) to the rear

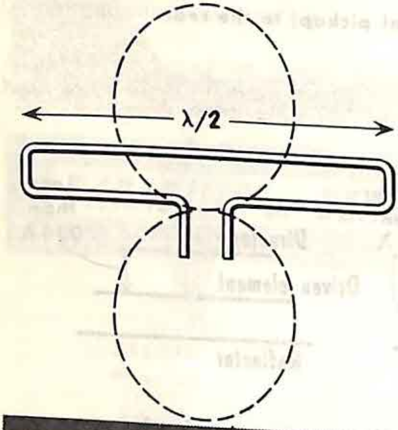


The greater the number of elements the narrower the beam and the greater the concentration of the energy

Because the current in the driven element is a combination of that received from the transmitter as well as from the parasitic element(s), the feedpoint impedance of the driven element is very much less than the 72 ohms of the resonant half-wave dipole. It can be as low as 25 ohms. Therefore it requires special methods of matching to the transmission line. Also, the behavior of the elements of the antenna as coupled circuits tends to narrow the band of frequencies around the resonant frequency which can be accepted by the antenna. A beam antenna tunes more sharply than a single resonant half-wave dipole. Usually the length of the director is 5% shorter than the driven element, while the reflector is 5% longer.

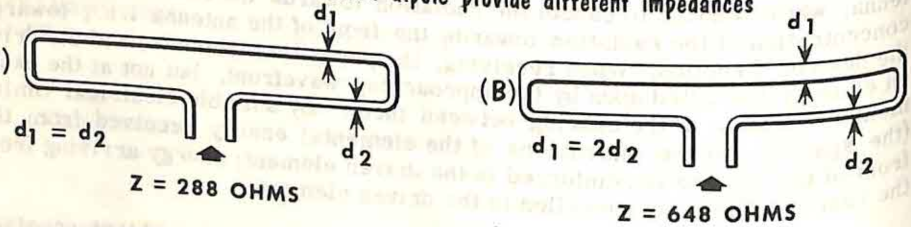
The Folded Dipole

A variation of the conventional half-wave dipole is the folded dipole. In effect it is two 1/2 λ dipoles – one a continuous rod, and the other split in the center – connected in parallel. The transmission line is connected to the split dipole. Its half-wave dimensioning is done exactly as for the ordinary half-wave dipole. Its behavior differs from the conventional half-wave dipole in several respects. The directivity of the folded dipole is bidirectional, but because of the distribution of the currents in the parts of the folded dipole its input impedance is very much higher. If all parts of the antenna are made of like diameter rod or tubing, the feedpoint impedance is 288 ohms. In this way it is an excellent match for 300-ohm twin-lead (ribbon) transmission line. Another characteristic of the folded dipole is that it is somewhat broader in the band of frequencies around resonance. Sometimes it is used as the driven element in parasitic antennas because the high impedance allows a reduction when used in the beam, while still being suitable for a match with a transmission line rated at from 50 to perhaps 75-ohms impedance.



THE FOLDED DIPOLE is bidirectional and a zero-db gain antenna. The amount of power it will accept from a transmitter is the same as for the ordinary half-wave dipole. Both will intercept the same amount of energy from an approaching wavefront.

Variations in the folded dipole provide different impedances

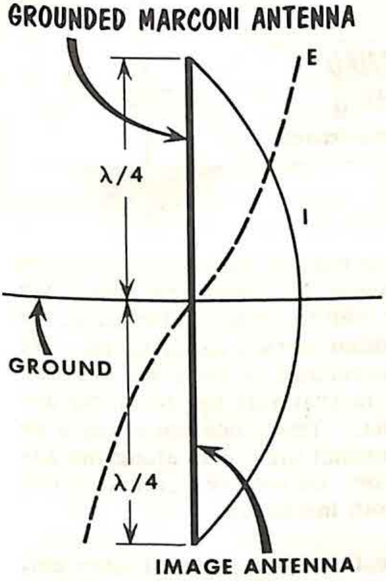


In general: $Z = 72\left(1 + \frac{d_1}{d_2}\right)^2$

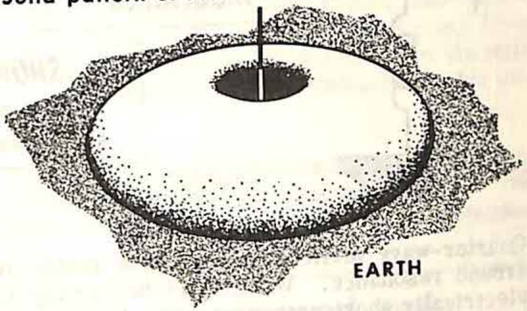
The Vertical Antenna

THE QUARTER WAVELENGTH (¼ λ) VERTICAL ANTENNA

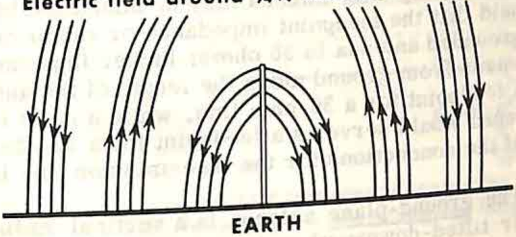
is an omnidirectional antenna. It radiates equally on all sides except upwards in line with the long axis



Solid pattern of radiation is equal all around

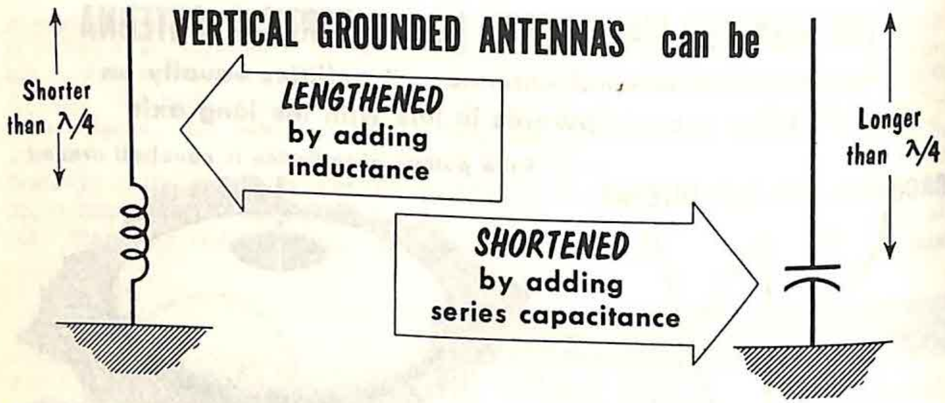


Electric field around ¼ λ vertical antenna



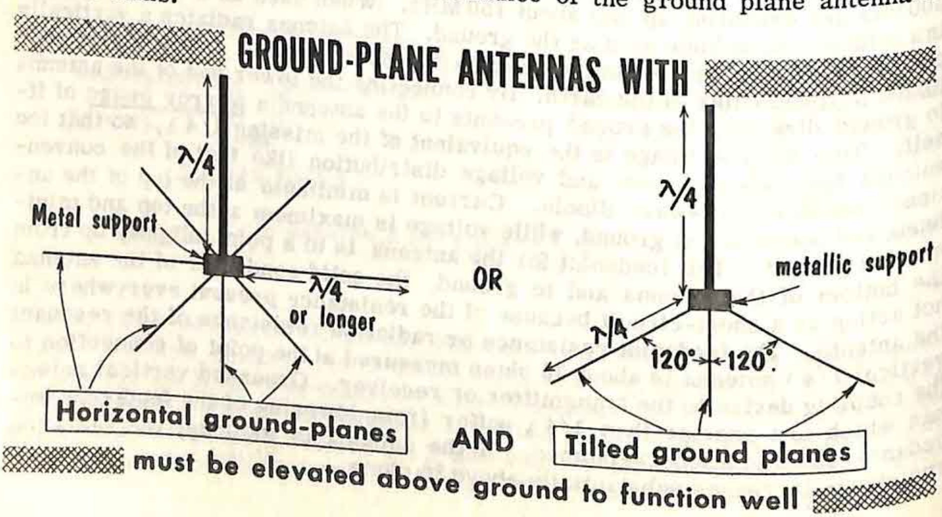
A standard form of antenna is the 1/4 λ vertical, also known as the Marconi antenna. It is a vertical rod or tube 1/4 λ long at the resonant frequency, and is "grounded" at the bottom. It is used for all frequencies beginning at about 500 kHz and extending up into about 150 MHz. When used as a "whip" antenna in a vehicle, the vehicle acts as the ground. The antenna radiates a vertically polarized wave at a low angle wherein the electric lines of force are positioned perpendicular to the earth. By connecting the lower end of the antenna to ground directly, the ground presents to the antenna a mirror image of itself. This mirror image is the equivalent of the missing 1/4 λ, so that the antenna then has a current and voltage distribution like that of the conventional resonant half-wave dipole. Current is minimum at the top of the antenna and maximum at ground, while voltage is maximum at the top and minimum at ground. The feedpoint for the antenna is to a point slightly up from the bottom of the antenna and to ground, the solid conductor of the antenna not acting as a short-circuit because of the resistance present everywhere in the antenna. The feedpoint resistance or radiation resistance of the resonant vertical 1/4 λ antenna is about 36 ohms measured at the point of connection to the coupling device to the transmitter or receiver. Grounded vertical antennas which are shorter than 1/4 λ suffer from lowering of the feedpoint impedance and radiation resistance. If the antenna is too long, the radiation resistance increases substantially above 36 ohms.

The Vertical Antenna (Cont'd)


VERTICAL GROUNDED ANTENNAS can be
Shorter than λ/4
LENGTHENED by adding inductance
SHORTENED by adding series capacitance
Longer than λ/4

Quarter-wave vertical antennas are usable over a narrow band of frequencies around resonance. When it is necessary to modify the electrical length the electrically short antenna may be lengthened by adding series inductance; the electrically long antenna may be shortened by adding series capacitance. We said that the feedpoint impedance or radiation resistance of the 1/4 λ vertical grounded antenna is 36 ohms; higher impedance is available by advancing upwards from ground along the length of the antenna. Thus, one point might be a feedpoint for a 36-ohm line, while a point somewhat higher up along the antenna would serve as a feedpoint for a 52-ohm line. Of course, ground is one of the connections for the transmission line in both instances.

The ground-plane antenna is a vertical radiator for which several straight, or tilted-downward rods extending outwards from the bottom of the radiator, act as the ground. These rods, approximating a 1/4 λ are the ground planes. In effect, they are an artificial ground sometimes referred to as a counterpoise, and are used as the ground point for the transmission line cables. The feedpoint impedance or radiation resistance of the ground plane antenna is about 30 ohms.

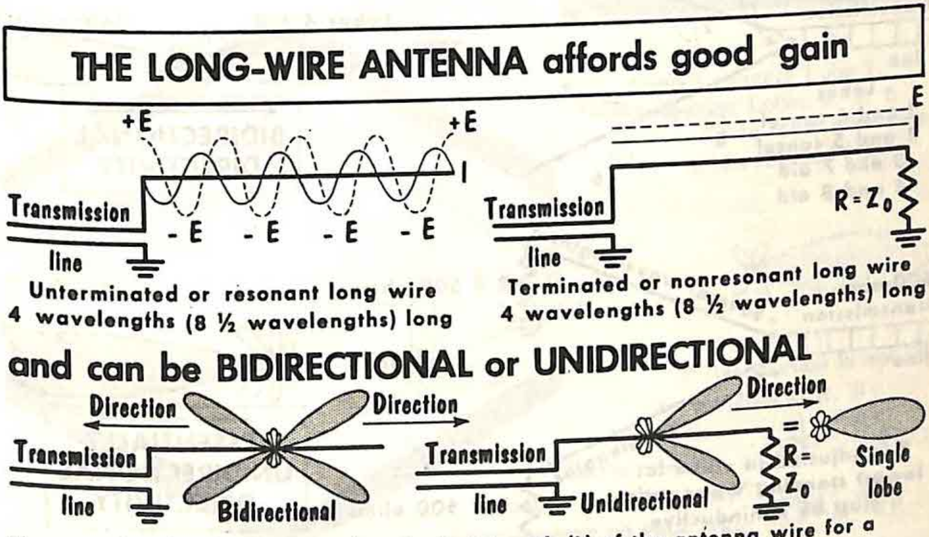


The Long-Wire Antenna

The long-wire antenna is a single long wire, usually two or more wavelengths (four or more 1/2 λ) long at the operating frequency. It is also known as an harmonic antenna. The greater the number of 1/2 λ the antenna length will accommodate for the operating frequency, the more effective the antenna as to gain over a zero-db gain half-wave dipole, and the better its directivity. It radiates a horizontally polarized wave at relatively low angles, from about 17° to perhaps 25° relative to the earth's surface. The gain varies from about 1.5 db when the antenna is four 1/2 λ long to about 4.5 db when the wire is sixteen 1/2 λ long. The long-wire antenna is end-fed, with a feedpoint impedance of 500-600 ohms.

Long-wire antennas are of two types – unterminated (resonant), and terminated in the characteristic impedance of the antenna (nonresonant). The resonant antenna has standing waves along its length. The voltage reverses its polarity every 1/2 λ, and the current reverses its direction. The terminated antenna has substantially uniform current flow in the antenna to the termination. Parallels to these electrical conditions are the resonant and nonresonant transmission lines.

THE LONG-WIRE ANTENNA affords good gain



Unterminated or resonant long wire 4 wavelengths (8 ½ wavelengths) long

Terminated or nonresonant long wire 4 wavelengths (8 ½ wavelengths) long

and can be BIDIRECTIONAL or UNIDIRECTIONAL

The equation for determining the physical length (L) of the antenna wire for a number of ½λ is

$$\text{length (feet)} = \frac{492\ (N-0.05)}{f\ (\text{MHz})}$$

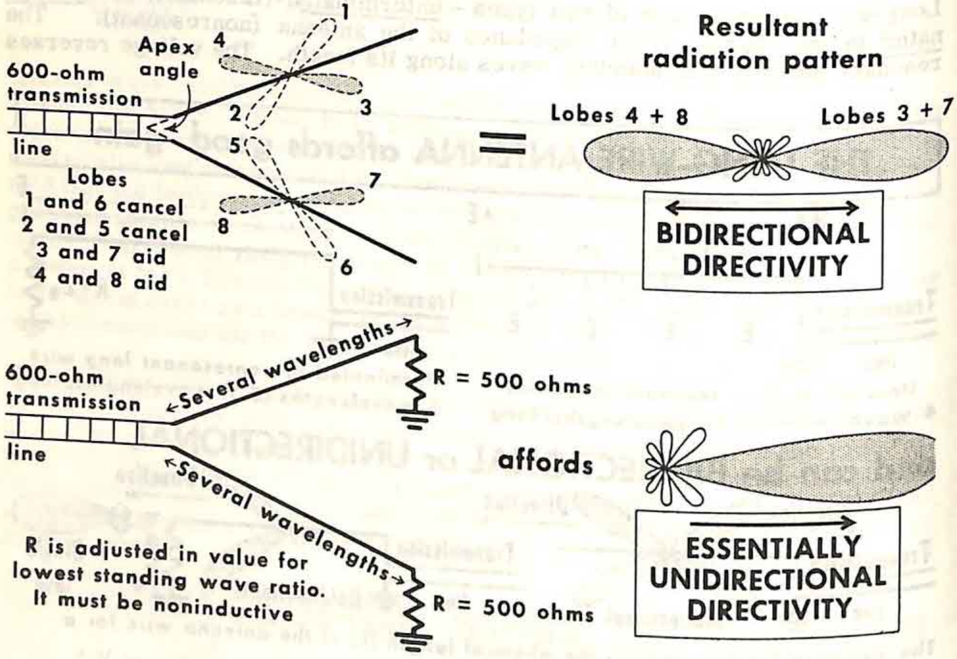
where N is number of ½λ

The essential difference in performance between the above two kinds of long-wire antennas is in the directivity. The resonant line is bidirectional at small angles to the long axis of the wire, while the terminated antenna is unidirectional in the direction towards the terminated end of the antenna. When the antenna length is five or more 1/2 λ at the operating frequency, some radiation takes place at right angles to the long axis of the antenna.

The V Antenna

The V antenna is a version of the long-wire antenna. It is the equivalent of two long wires (legs) arranged in the form of a flat V, each wire being fed with a voltage 180° out of phase with the other. The advantages of this antenna are gain and directivity. It is achieved by cancellation between oppositely directed corresponding radiation lobes in each leg, and by aiding action between similarly directed corresponding lobes in each leg. The final result is a bidirectional radiation pattern in which the lobes are much narrower than for the single long wire. Gain achieved with the V antenna is about twice that for the single long wire, which has a length equal to that of the legs of the V. Almost 12-db gain over a half-wave dipole is realized when each leg of the V is 8 λ long. The angle made at the apex of the figure is important. This angle varies from about 35° for the 8-λ structure to about 70° for the 2-λ wires. When the antenna is to be used over a wide range of frequencies, the apex angle is made the average between the optimum for the lowest and highest frequencies in terms of the number of 1/2 λ in each leg. At the lowest frequency the legs should be several wavelengths long. If each leg is terminated in a resistance of about 500 ohms the radiation pattern becomes unidirectional.

THE V ANTENNA has HIGH GAIN AND A CHOICE of BIDIRECTIONAL or UNIDIRECTIONAL DIRECTIVITY

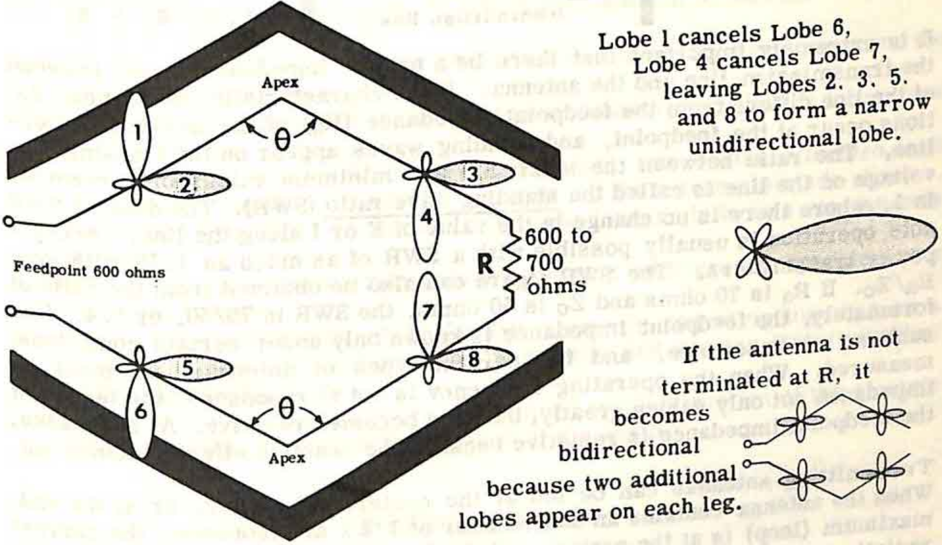


1
Apex angle
4
600-ohm transmission line
3
2
5
7
8
6
Lobes
1 and 6 cancel
2 and 5 cancel
3 and 7 aid
4 and 8 aid
Resultant radiation pattern
Lobes 4 + 8
Lobes 3 + 7
BIDIRECTIONAL DIRECTIVITY
600-ohm transmission line
Several wavelengths
R = 500 ohms
affords
Several wavelengths
R is adjusted in value for lowest standing wave ratio. It must be noninductive
R = 500 ohms
ESSENTIALLY UNIDIRECTIONAL DIRECTIVITY

The Rhombic Antenna

The rhombic is a very efficient antenna of broad frequency capability, and is prominent in all radio communication facilities where the space necessary for the large structure is available. It can be said to be a double V, in which case it becomes a diamond-shaped structure lying in the horizontal plane. It can be terminated or unterminated, the difference between the two being directivity. When used, the terminating resistance is between 600 and 700 ohms, noninductive, and both types are fed by open lines of 600 ohms characteristic impedance. Its advantages become evident when each leg of the rhombic is several wavelengths long, and if the angle θ at the apex is between 50° and 70°. In this event the antenna shows a power gain of from 8 to 12 db over a conventional half-wave dipole. When terminated, the radiation pattern is unidirectional in the direction of the terminated end, and has a very narrow principal lobe. Because of this behavior the antenna must be laid out so that it is pointing in the desired direction of communication. It can be made bidirectional simply by removing the terminating resistance. It is an excellent antenna for operation over a wide band of frequencies, especially if the leg lengths are between 5 and 6 λ long at the lowest frequency of operation. Little is gained by making each leg longer than about 8 λ.

THE RHOMBIC ANTENNA

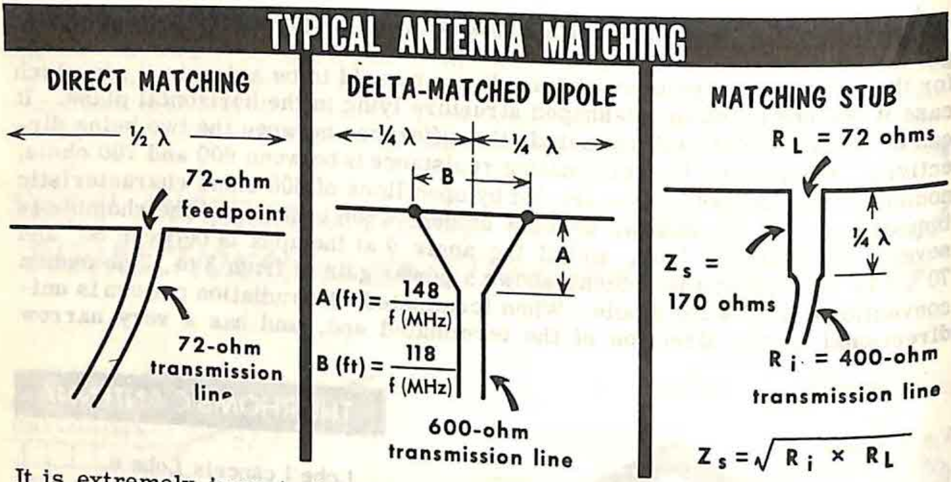


Lobe 1 cancels Lobe 6,
Lobe 4 cancels Lobe 7,
leaving Lobes 2, 3, 5,
and 8 to form a narrow
unidirectional lobe.

If the antenna is not
terminated at R, it
becomes
bidirectional
because two additional
lobes appear on each leg.

The highly directional characteristic of the rhombic arises from the fact that two principal lobes develop in each leg of the terminated arrangement, and from the condition that one lobe in each leg cancels the corresponding oppositely directed lobe in the other leg. This leaves four lobes pointing in the same direction, one in each leg. These are additive, and produce a single narrow lobe in the forward direction.

Feeding the Antenna (SWR)



It is extremely important that there be a proper impedance match between the transmission line and the antenna. If the characteristic impedance (Z_o) of the line differs from the feedpoint impedance (R_a) of the antenna, reflections occur at the feedpoint, and standing waves appear on the transmission line. The ratio between the maximum and minimum values of current or voltage on the line is called the standing wave ratio (SWR). The desired SWR is 1, where there is no change in the value of E or I along the line. Acceptable operation is usually possible with a SWR of as much as 1.75 with low-power transmitters. The SWR figure can also be obtained from the ratio of R_a/Z_o. If R_a is 70 ohms and Z_o is 50 ohms, the SWR is 70/50, or 1.4. Unfortunately, the feedpoint impedance is known only under certain conditions, such as at resonance, and for certain types of antennas, or must be measured. When the operating frequency is not at resonance, the feedpoint impedance not only varies greatly, but also becomes reactive. At resonance, the feedpoint impedance is resistive because the reactive effects balance out.

Transmitting antennas can be fed at the center, off center, or at the end. When the antenna contains an odd number of 1/2 λ at resonance, the current maximum (loop) is at the center, and the feedpoint impedance is equal to the radiation resistance, which in turn is a function of the number of 1/2 λ in the conductor. This is so at any point along the antenna where a current loop exists. When the antenna contains an even number of 1/2 λ at the resonant frequency, current loops appear on both sides of center. A feedpoint can be located at any current loop. However, it is only in the case of the half-wave dipole operated at resonance that the impedance at the center is 72 ohms. Antennas containing two or more 1/2 λ can be fed at the end – a high-impedance point. The high transmission-line impedance required for end-feeding can be obtained through a resonant line, or a 1/4 λ open line cut for the operating frequency, to act as an impedance transformer between the transmission line and antenna. With the parasitic array, the feedpoint must be determined by experiment. It is difficult to state a dimension each side of the center of the driven element that will serve as the connecting points for any given Z_o of the transmission line used.

A transmission line is a device for guiding electrical energy from one point to another. Such a line has electrical constants of inductance, capacitance, and resistance distributed along its length.

A line terminated in a resistance equal to its characteristic impedance is said to be terminated correctly.

The ratio of maximum to minimum voltage or current along a transmission line is called the standing wave ratio – this is a measure of the energy reflected.

A properly matched line is nonresonant. It produces no reflection of energy and there are no standing waves – there is maximum transmission of energy.

A delta-matching section used with a two-wire line is made by fanning out the end of the transmission line as it approaches the antenna.

Electromagnetic waves are propagated into space at nearly the speed of light, 300,000,000 meters per second, or 186,000 miles per second.

A radio wave may be described as a moving electromagnetic field, having velocity in the direction of travel.

The wavelength of a radio wave in free space is equal to its velocity divided by its frequency ($\lambda = V/f$).

The energy received at a distant point is the sum of the direct wave and the ground-reflected wave.

The velocity of wave travel on an antenna or transmission line is lower than in free space.

If an antenna is cut to a length of exact resonance, the reactance is zero, and the antenna impedance is purely resistive. If the antenna is made shorter, capacitive reactance is present; if made longer, inductive reactance is present.

A quarter-wave antenna operating in conjunction with ground operates as a resonant antenna.

An array is a combination of half-wave elements operating together as a single antenna. Arrays provide more gain and greater directivity than single-element antennas.

The polarization of a radio wave is determined by the direction of the electric flux lines with respect to the surface of the earth.

REVIEW QUESTIONS

1. What is meant by electromagnetic energy?
2. What is meant by ground, ground-reflected, and direct waves?
3. What is meant by skip distance?
4. What is the function of a transmission line?
5. Name three different types of transmission line.
6. What is meant by a wavelength?
7. What is an antenna?
8. What is meant by radiation resistance?
9. What is meant by the characteristic impedance of a transmission line?
10. What is the function of a parasitic element?
11. Explain the term polarization as applied to an electromagnetic wave.
12. What is the current and voltage distribution on a grounded quarter-wave antenna?

GLOSSARY

Amplitude Modulation: A system of transmission and reception of intelligence in which the amplitude of the carrier is made to vary in accordance with the intelligence.

Antenna: A device used to radiate or absorb r-f energy.

Array: An arrangement of antenna elements, usually dipoles, which results in desirable directional characteristics.

Attenuation: The reduction in the strength of a signal.

Breakdown Voltage: The voltage at which an insulator dielectric ruptures, or at which ionization and conduction take place in a gas or vapor.

Buffer Amplifier: An amplifier used to isolate the output of an oscillator from the effects produced by changes in voltage or loading in following circuits.

Carrier: The r-f component of a transmitted wave upon which an audio signal or other form of intelligence can be impressed.

Characteristic Impedance: The ratio of the voltage to the current at every point along a transmission line on which there are no standing waves.

Coaxial Cable: A transmission line consisting of two conductors concentric with and insulated from each other.

Continuous Waves (CW): Radio waves that maintain a constant amplitude and a constant frequency.

Coupling: The association of two circuits in such a way that energy may be transferred from one circuit to another.

Crystal: A natural substance, such as quartz or tourmaline, which is capable of producing a voltage stress when under pressure, or producing pressure when under an applied voltage. Under stress, it has the property of responding only to a given frequency when cut to a given thickness.

Dipole Antenna: Two metallic elements, each approximately one quarter wavelength long, which radiate r-f energy fed to them by the transmission line.

Director: A parasitic antenna placed in front of a radiating element so that r-f radiation is aided in the forward direction.

Electromagnetic Field: A space field in which electric and magnetic vectors at right angles to each other travel in a direction at right angles to both.

Electrostatic Field: A field of influence between two charged bodies.

Field Intensity: Electrical strength of a field.

Feedback: A transfer of energy from the output circuit of a device back to its input.

Filter: A combination of circuit elements designed to pass a definite range of frequencies, attenuating all others.

Frequency: The number of complete cycles per second existing in any form of wave motion; such as the number of cycles per second of alternating current.

Frequency Distortion: Distortion that occurs as a result of failure to amplify or attenuate equally all frequencies present in a complex wave.

Frequency Modulation: A system of transmission and reception of intelligence in which the carrier-wave frequency is made to vary in accordance with variations in the modulating signal.

Frequency Stability: The ability of an oscillator to maintain its operation at a constant frequency.

Grid Current: Current which flows between cathode and the grid whenever the grid becomes positive with respect to the cathode.

Ground: A metallic connection with the earth to establish ground potential. Also, a common return to a point of zero r-f potential, such as the chassis of a receiver or a transmitter.

Harmonic: An integral multiple of a fundamental frequency. (The second harmonic is twice the frequency of the fundamental or first harmonic.)

Harmonic Distortion: Amplitude distortion.

Interelectrode Capacitance: The capacitance existing between the electrodes in an electron tube.

Ionization Potential: The lowest potential at which ionization takes place within a gas-filled tube.

Ionosphere: A region composed of highly ionized layers of atmosphere from about 70 to 250 miles above the surface of the earth.

Matched Impedance: The condition that exists when two coupled circuits are so adjusted that their impedances are equal.

Modulation: The process of varying the amplitude (AM), the frequency (FM), or the phase (PM) of a carrier wave in accordance with other signals to convey intelligence.

Modulator: The circuit which provides the signal that varies the amplitude, frequency, or phase of the oscillations generated in the r-f portion of the transmitter.

Neutralization: The process of nullifying the voltage fed back through the interelectrode capacitance of an amplifier tube, by providing an equal voltage of opposite phase; generally necessary only with triode tubes.

Node: A zero point; specifically, a current node is a point of zero current, and a voltage node is a point of zero voltage.

Oscillator: A circuit capable of converting dc into ac of a frequency determined by the constants of the circuit.

Oscilloscope: An instrument for showing, visually, graphical representations of the waveforms encountered in electrical circuits.

Parallel Feed: Application of a d-c voltage to the plate or grid of a tube in parallel with an a-c circuit so that the d-c and a-c components flow in separate paths. Also called *shunt feed.*

Parasitic Suppressor: A resistor in an electron tube circuit to prevent unwanted oscillations.

Piezoelectric Effect: The effect of producing a voltage by placing a stress, either by compression, expansion, or twisting, on a crystal, and, conversely, the effect of producing a stress in a crystal by applying a voltage to it.

Plate Dissipation: The power in watts consumed at the plate in the form of heat.

Plate Efficiency: The ratio of the a-c power output from a tube to the average d-c power supplied to the plate circuit.

Plate Modulation: Amplitude modulation of a class-C r-f amplifier by varying the plate voltage in accordance with the signal.

Radiation Resistance: A fictitious resistance which may be considered to dissipate the energy radiated from the antenna.

Reflector: A metallic object placed behind a radiating antenna to prevent r-f radiation in an undesired direction and to reinforce radiation in a desired direction.

Screen Dissipation: The power dissipated in the form of heat on the screen grid as the result of bombardment by the electron stream.

Series Feed: Application of the d-c voltage to the plate or grid of a tube through the same impedance in which the ac flows.

Standing Wave: A distribution of current and voltage on a transmission line formed by two sets of waves traveling in opposite directions, and characterized by the presence of a number of points of successive maxima and minima in the distribution curves.

Thermocouple Ammeter: An ammeter that operates by means of a voltage produced by the heating effect of a current passed through the junction of two dissimilar metals. It is used for r-f measurements.

Unbalanced Line: A transmission line in which the voltages on the two conductors are not equal with respect to ground: for example, a coaxial line.

Wave: Basically, an electromagnetic impulse, periodically changing in intensity and traveling through space. Also, the graphical representation of the intensity of that impulse over a period of time.

Wavelength: The distance, usually expressed in meters, traveled by a wave during the time interval of one complete cycle. It is equal to the velocity divided by the frequency.

Wave Propagation: The transmission of r-f energy through space.

INDEX

vol. 6

(*Note:* A cumulative index covering all six volumes in this series is included at the end of this volume.)

AM-CW transmitter, 6-92
Amplifiers
  bias voltage, 6-58
  buffer, 6-37
  Class-B linear, 6-106
  Class-C. *See* Class-C amplifier
  driver, 6-45
  final, 6-45
  linear, 6-106
  modulator driver, 6-86
  power. *See* Power amplifier
  push-pull, 6-52
  speech, 6-84
  tuned r-f, 6-45, 6-46
Amplitude modulation (AM), 6-69
  bandwidth, 6-72
  modulation envelope, 6-69
  percent modulation, 6-70, 6-71
  sideband power, 6-73
  sidebands, 6-72
  transmission, 6-69
  transmitter, 6-74
  wave power distribution, 6-73
Angle of radiation, 6-140
Anode, 6-6
Antennas
  beam type, 6-148
  delta-match, 6-156
  dipole, 6-141
  directivity pattern, 6-147
  director element, 6-148
  doublet, 6-141
  driven element, 6-148
  feeding, 6-156
  feedpoint impedance, 6-146
  folded dipole, 6-150
  fundamental type, 6-141
  ground-plane, 6-152
  half-wave dipole. *See* Half-wave dipole
  half-wave doublet, 6-141
  half-wave voltage distribution, 6-144
  half-wavelength dimension, 6-142
  impedance, 6-145, 6-146
  long-wire, 6-153
  Marconi, 6-151
  matching, 6-156
Antennas (*continued*)
  matching stub, 6-156
  parasitic array, 6-148, 6-149
  radiation resistance, 6-146
  reflector element, 6-148
  resistance, 6-145
  rhombic, 6-155
  standing wave ratio (SWR), 6-127, 6-156
  V-type, 6-154
  vertical, 6-151
  wavelength, 6-142
  Yagi, 6-148
Armstrong phase-modulation circuit, 6-97
AT-cut crystal, 6-21
Automatic limit control (ALC), 6-91

Backwave, 6-63
Balanced-bridge modulator, 6-101
Balanced-modulator, 6-97, 6-100
Bandpass filter, 6-102
Bandwidth, 6-72
Barium titanate crystal, 6-82
Beam antenna, 6-148
Bias voltages, 6-58
Blocked-grid keying, 6-65
BT-cut crystal, 6-21
Buffer amplifier, 6-37
Butler overtone oscillator, 6-27

Calorimeter, 6-60
Carbon microphone, 6-82
Carrier, 6-63
Carrier suppression, 6-100
Cathode emitter, 6-4
Cathode keying, 6-64
CCS ratings, 6-8
Ceramic microphone, 6-82
Ceramic tubes, 6-7
Characteristic impedance, 6-120, 6-121
Chirp, 6-63
Choke modulation, 6-76
Citizens Band transceiver, 6-116
Clapp oscillator, 6-16, 6-17
Class-B linear amplifier, 6-106

Class-C amplifier, 6-31
  grid circuit, 6-34
  plate circuit, 6-35
  transistor, 6-36
  tuned r-f, 6-34
Coaxial cable, 6-119
Colpitts oscillator, 6-16
Compressional crystal mode, 6-22
Control grid, 6-5
  modulation, 6-78
  ratings, 6-5
Continuous wave (CW), 6-3
Coupling, 6-43
Cross-neutralization, 6-48
Crystals
  action, 6-19
  axes, 6-20
  basic oscillator, 6-25
  characteristics, 6-24
  circuit, 6-24
  cuts, 6-20
  filter, 6-103
  harmonics, 6-22
  holder, 6-23
  lattice filter, 6-104
  microphone, 6-82
  oven, 6-23
  overtone oscillator, 6-27
  temperature coefficient, 6-21
  wafer, 6-20
Current loops, 6-126
Current nodes, 6-126
CW, 6-3, 6-63
CW-AM transmitter, 6-92
CW transmitter, 6-45, 6-67

Damped oscillations, 6-12
Dc-to-dc converter, 6-111
Dead-man's stick, 6-109
Delta-match, 6-156
Diode harmonic generator, 6-41
Dipole, 6-141
Direct FM, 6-94
Direct waves, 6-136, 6-137
Directivity pattern, 6-147
Director element, 6-148
Double sideband, 6-101
Doublet, 6-141
Driven element, 6-148
Driver stage, 6-45
Driving power, 6-5
Dummy load, 6-60
Dynamic microphone, 6-83

Electric fields in free space, 6-133
Electric lines of force, 6-135
Electrical wavelength, 6-125
Electromagnetic energy, 6-134
Electromagnetic field, 6-133
Electromagnetic wave, 6-133
Emitter, 6-4
External anode, 6-7

Feedpoint impedance, 6-146
Final amplifier, 6-45
Flexure crystal mode, 6-22
Folded dipole antenna, 6-150
Free-space wave, 6-134
Frequency, 6-134
Frequency doubler, 6-39, 6-41
Frequency modulation (FM), 6-94
Frequency multiplier, 6-38
  amplifier, 6-39
  tuning, 6-42
Frequency quadrupler, 6-39
Frequency tripler, 6-39, 6-41
Fundamental antenna, 6-141
Fundamental frequency, 6-22, 6-35

Gas-filled rectifier diode, 6-9
Grid-bias modulation, 6-78
Grid drive, 6-34
Grid neutralization, 6-47
Grid tank, 6-34, 6-51
Ground plane antenna, 6-152
Ground-reflected waves, 6-137
Ground waves, 6-136, 6-137

Half-wave dipole, 6-141
  current distribution, 6-144
  directivity, 6-147
  resonance, 6-143
  voltage distribution, 6-144
Half-wave doublet, 6-141
Half-wavelength dimension, 6-142
Harmonic frequencies, 6-35
Harmonic generator, 6-41
Harmonics, 6-22, 6-40
Hartley oscillator, 6-15, 6-17
Heising modulation, 6-76
Horizontal polarization, 6-133

ICAS ratings, 6-8
Impedance mismatch, 6-127
Indirect FM, 6-96
Inductive neutralization, 6-48
Input circuit, 6-50
Input power, 6-46, 6-60
Insertion loss, 6-104
Ionizing potential, 6-10
Ionosphere, 6-139

Kennely-Heaviside layer, 6-139
Key clicks, 6-63
  filter, 6-65
Keyer tube, 6-64
Keying, 6-63
  backwave, 6-63
  blocked-grid, 6-65
  cathode, 6-64
  chirp, 6-63
  CW, 6-63
  plate, 6-66

Keying (*continued*)
  relay, 6-64
  screen-grid, 6-66
  telegraphy, 6-63, 6-66

L-network, 6-57
  tuning, 6-62
Lambda, 6-124
Lattice-type filter, 6-104
Linear amplifier, 6-106
Lines of force, 6-132
Line-of-sight propagation, 6-138
Line-of-sight reception, 6-137
Longitudinal crystal mode, 6-22
Long-wire antenna, 6-153

Magnetic fields in free space, 6-133
Magnetic lines of force, 6-135
Marconi antenna, 6-151
Matching stub, 6-156
Mercury-vapor rectifier diode, 6-9
Metering, 6-59
Microphones, 6-82, 6-83
Modulate, 6-69
Modulated r-f amplifier, 6-74
Modulation, 6-74
  checking, 6-81
  choke, 6-76
  control-grid, 6-78
  envelope, 6-69
  grid-bias, 6-78
  Heising, 6-76
  levels, 6-75
  plate, 6-76, 6-77, 6-88
  r-f amplifier, 6-74
  screen grid, 6-80
  stages, 6-86
  transformer, 6-77
Modulator, 6-74
Modulator driver, 6-86
Modulator stages, 6-88
Moving coil microphone, 6-83

Neutralization, 6-42, 6-47
Non-linear mixing circuit, 6-69

Open-wire transmission line, 6-119
Oscillators, 6-11
  basic circuit, 6-13
  characteristics, 6-14
  Clapp, 6-16, 6-17
  Colpitts, 6-16
  coupling, 6-29
  crystal, 6-19 to 6-27
  harmonics, 6-22
  Hartley, 6-15, 6-17
  loading, 6-29
  losses, 6-12
  Pierce, 6-26

Oscillators (*continued*)
  regenerative feedback, 6-13
  shock excitation, 6-14
  transistor, 6-17
  tuned-plate tuned-grid (TPTG), 6-18
  variable frequency oscillator (VFO), 6-28
Output circuits, power amplifier, 6-55
Output coupling, 6-56
Output coupling networks, 6-57
Output power, 6-60
Output-signal power, 6-6
Overload relay circuit, 6-113
Overtones. *See* Harmonics

Parasitic array, 6-148, 6-149
Parasitic oscillation, 6-89
Percent modulation, 6-70, 6-71
Phasing method of sideband removal, 6-105
Phase modulation, 6-94, 6-98
Pi network, 6-53, 6-57
  tuning, 6-62
Pie winding, 6-44
Pierce oscillator, 6-26 .
Piezoelectric effect, 6-19, 6-82
Plate, 6-6
Plate keying, 6-66
Plate modulation, 6-76, 6-77, 6-88
Plate neutralization, 6-47
Plate power input, 6-6
Plate tank, 6-34, 6-55
Positive ions, 6-10
Power amplifier, 6-45, 6-46
  bias voltages, 6-58
  grid-tank circuit, 6-51
  input circuit, 6-50
  output circuit, 6-55
  push-pull, 6-54
  single-ended, 6-53
Power distribution in AM wave, 6-73
Propagation
  angle of radiation, 6-140
  direct waves, 6-136, 6-137
  electric fields in free space, 6-133
  electric lines of force, 6-135
  electric wavelength, 6-125
  electromagnetic, 6-133, 6-134
  free-space wave, 6-134
  frequency, 6-134
  ground-reflected waves, 6-137
  ground waves, 6-136, 6-137
  horizontal polarization, 6-133
  ionosphere, 6-139
  Kennely-Heaviside layer, 6-139
  lines of force, 6-132
  line-of-sight, 6-137, 6-138
  magnetic, 6-133, 6-135
  radiation, 6-132
  radiation polarization, 6-133
  radio wave, 6-133
  refraction, 6-139
  skip distance, 6-140
  sky waves, 6-136, 6-139

Propagation (*continued*)
  temperature inversion, 6-138
  velocity, 6-134
  velocity of propagation, 6-125
  vertical polarization, 6-133
  vertical radiation, 6-136
  wavefront, 6-135
  wavelength, 6-125, 6-134
  wave propagation, 6-136
Push-pull amplifier, 6-52
Push-pull frequency multiplier, 6-42
Push-pull power amplifier, 6-54

Q, 6-12
Quartz crystal, 6-19

Radiation, 6-132
  polarization, 6-133
  resistance, 6-146
Radio communication, 6-1
Radio signals, 6-2
Radiotelegraphy, 6-3
Radio wave, 6-133
Reactance tube circuit, 6-94
Rectifier tube, 6-9
Reflector element, 6-148
Refraction, 6-139
Regenerative feedback, 6-13
Resonant transmission line, 6-128, 6-129
R-f choke, 6-44
R-f excitation, 6-5
Rhombic antenna, 6-155
Ribbon lead, 6-119
Ribbon microphone, 6-83
Rochelle salt crystal, 6-9
Running-time meter, 6-59

Screen-grid keying, 6-66
Screen-grid modulation, 6-80
Shear mode, 6-22
Shock excitation, 6-14
Shorting stick, 6-109
Sidebands, 6-72
Sideband power, 6-73
Sideband suppression, 6-102
Single-ended power amplifier, 6-53
Skip distance, 6-140
Sky waves, 6-136, 6-139
Snap diode, 6-41
Snap-off diode, 6-41
Solenoid winding, 6-44
Speech amplifiers, 6-84
Speech clipping and filtering, 6-90
Split stator capacitor, 6-53
SSB (Single Sideband)
  balanced bridge modulator, 6-101
  balanced modulator, 6-97, 6-100
  bandpass filter, 6-102
  basics, 6-99
  carrier suppression, 6-100

SSB (Single Sideband) (*continued*)
  crystal filter, 6-103
  crystal lattice filter, 6-104
  double-sideband, 6-101
  insertion loss, 6-104
  lattice type filter, 6-104
  phasing method of sideband removal, 6-105
  sideband suppression, 6-102
  suppressed carrier, 6-100
  transmitters, 6-107
Standing waves, 6-127
Standing wave ratio (SWR), 6-127, 6-156
Step-recovery diode, 6-41
Suppressed carrier, 6-100
Surge impedance, 6-121

Telegraphy, 6-63, 6-66
Temperature coefficient, crystal, 6-21
Temperature inversion, 6-138
Thermocouple-type ammeter, 6-60
Tourmaline crystal, 6-19
Transceiver, 6-116
Transistor oscillators, 6-17
Transistor r-f amplifier neutralization, 6-49
Transition time, 6-41
Transmission lines, 6-118
  characteristic impedance, 6-120, 6-121
  coaxial cable, 6-119
  coupling, 6-56
  current loop, 6-126
  current node, 6-126
  fields, 6-123
  impedance, 6-120
  impedance mismatch, 6-127
  line mismatch, 6-127
  open-circuited, 6-128
  open-end, 6-128
  open-wire line, 6-119
  resonant transmission line, 6-128, 6-129
  ribbon lead, 6-119
  section applications, 6-131
  section properties, 6-130
  short-circuited, 6-129
  standing waves, 6-127
  standing wave ratio (SWR), 6-127, 6-156
  surge impedance, 6-121
  terminated, 6-122
  termination, 6-122, 6-126
  twin lead, 6-119
  types, 6-119
  velocity of propagation, 6-125
  velocity propagation constant, 6-125
Transmitters
  AM, 6-74
  controls, 6-112
  control system, 6-115
  CW, 6-45, 6-67
  CW-AM, 6-92
  fundamental, 6-3
  metering, 6-59
  power supply, 6-108
  SSB, 6-107

Transmitting tubes, 6-4, 6-8
Tubes
  anode, 6-6
  cathode emitter, 6-4
  ceramic, 6-7
  control grid, 6-5
  control grid ratings, 6-5
  driving power, 6-5
  emitter, 6-4
  external anode, 6-7
  gas-filled rectifier, 6-9
  mercury-vapor rectifier diode, 6-9
  output-signal power, 6-6
  ratings, 6-8
  rectifier, 6-9
  r-f excitation, 6-5
  transmitting, 6-4
  plate, 6-6
  plate power input, 6-6
  Xenon-filled rectifier diode, 6-9
Tuned-plate tuned-grid (TPTG) oscillator, 6-18
Tuned r-f amplifier, 6-45
Tuned r-f power amplifier, 6-46
Tuning procedures, 6-61
Twin lead, 6-119

Unilateralization, 6-49

V-antenna, 6-154
Variable-frequency oscillator (VFO), 6-28
Velocity, 6-134
Velocity microphone, 6-83
Velocity of propagation, 6-125
Velocity propagation constant, 6-125
Vertical antenna, 6-151
Vertical polarization, 6-133
Vertical radiation, 6-136

Wavefront, 6-135
Wavelength, 6-124, 6-125, 6-134, 6-142
Wave propagation, 6-136

X-cut crystal, 6-20
Xenon-filled rectifier diode, 6-9

Yagi antenna, 6-148
Y-cut crystal, 6-20

CUMULATIVE INDEX

(*Note:* The first number of each entry identifies the volume in which the information is to be found; the second number identifies the page.)

A-c (alternating current), 2-1
  generator, 2-10
  in inductor, 2-39
  instantaneous value, 2-14
  introduction to, 2-1
  magnetic field, 2-22
  meters, 2-132
  in parallel R-L circuits, 2-43
  peak value, 2-14
  power, 2-92
  in R-L circuits, 2-35
  in R-L series circuits, 2-35, 2-40
Acceptor, 5-5
A-c—d-c power supply, 3-45
A-c—d-c superheterodyne receiver, 4-39
A-c plate resistance, 3-20
Adjustable bandwidth, 4-46
AFC (automatic frequency control), 4-110
Air-core transformer, 2-51
ALC (automatic limit control), 6-91
Alignment, 4-40
Alnico, 1-100
Alpha, 5-18
  cutoff frequency, 5-21
Alternating current. *See* A-c
Alternating voltage, 2-1
  in R-L circuits, 2-35
Alternation, 2-12
Altitude, 2-3
Aluminum, 1-30
AM (amplitude modulation), 3-129, 4-63, 6-69
  bandwidth, 6-72
  modulation envelope, 6-69
  percent modulation, 6-70, 6-71
  sideband power, 6-73
  sidebands, 6-72
  transmission, 6-69
  transmitter, 6-74
  wave power distribution, 6-73
Amber, 1-2
AM-CW transmitter, 6-92
American Wire Gage, 1-61, 1-139
AM-FM superheterodyne receiver, 5-58
Ammeter, 1-75, 1-127
  thermocouple-type, 6-60
Ampere, 1-36
  Andre Marie, 1-36
  hour, 1-50
  turns, 1-112, 1-115, 2-53
Amplification, 3-56
  calculation, 3-66
  factor, 3-19, 5-18
  r-f, 3-109
  voltage, 3-66
Amplifier(s)
  audio driver, 5-53
  audio frequency, 3-75
  bias voltage, 6-58
  buffer, 6-37
  cathode follower, 3-89
  Class-A, 3-70, 3-99
  Class-AB, 3-72
  Class-B, 3-71, 3-100, 6-106
  Class-C. *See* Class-C amplifier
  common base, 5-24, 5-25
  common collector, 5-24, 5-29
  common emitter, 5-24, 5-27
  complementary symmetry push-pull, 5-56
  coupling, 3-81—3-90, 3-111
  decibel, 3-77
  decoupling, 3-90
  differential, 4-53, 5-72
  distortion, 3-76, 3-98
  double-ended output stage, 5-55
  driver, 6-45
  dynamic characteristics, 3-57
  final, 6-45
  feedback, 3-103
  frequency response, 3-79
  grid-bias, 3-63, 3-73, 3-74, 3-115
  grounded-base, 5-24
  grounded-collector, 5-24
  grounded-emitter, 5-24
  grounded-grid, 3-88
  grounded-plate, 3-89
  I-F, 4-26, 4-27, 4-81, 5-49
  impedance matching, 3-101
  linear, 5-72, 5-73, 6-106
  load line, 3-59
  loop, 4-36
  modulator driver, 6-86
  multi-purpose linear, 5-73
  operating point, 3-64, 3-70
Amplifier(s) *(continued)*
  paraphase, 3-93
  phase inverter, 3-91—3-93
  phase relationships, 3-67
  power. *See* Power amplifier
  preamplifier, 5-39
  push-pull. *See* Push-pull amplifier
  r-f, 4-18, 4-77, 5-43, 6-45, 6-46, 6-74
  single-ended output, 5-54
  single-ended power, 6-53
  speech, 6-84
  tuned r-f, 6-45, 6-46
  voltage, 3-56, 3-75
Amplitude
  distortion, 3-76
  modulation. *See* AM
Angle of radiation, 6-140
Angular rotation, 2-2
Anode, 3-5, 6-6
Antenna(s)
  beam type, 6-148
  circuits, 4-5
  delta match, 6-156
  dimensions, 4-75
  dipole, 6-141
  directivity pattern, 6-147
  director element, 6-148
  doublet, 6-141
  driven element, 6-148
  feeding, 6-156
  feedpoint impedance, 6-146
  ferri-loopstick, 4-36
  ferrite-rod, 5-43
  FM receiving, 4-74
  folded dipole, 4-75, 6-150
  fundamental type, 6-141
  ground-plane, 6-152
  half-wave dipole. *See* Half-wave dipole antenna
  half-wave doublet, 6-141
  half-wavelength dimension, 6-142
  half-wave voltage distribution, 6-144
  impedance, 6-145
  input impedance, 6-146
  loop, 4-36

- Antenna(s) *(continued)*
  - long-wire, 6-153
  - Marconi, 6-151
  - matching, 6-156
  - parasitic array, 6-148, 6-149
  - radiation resistance, 6-146
  - reflector element, 6-148
  - resistance, 6-145
  - rhombic, 6-155
  - standing wave ratio (SWR), 6-127, 6-156
  - transformer, 4-6
  - V-type, 6-154
  - vertical, 6-151
  - wavelength, 6-142
  - Yagi, 6-148
- Antimony, 5-2, 5-4
- Apparent power, 2-93
- Arc, 1-19
- Armature, 1-114, 1-117, 2-10
- Armstrong oscillator, 3-116
- Armstrong phase-modulation circuit, 6-97
- A-supply, 3-7
- AT-cut crystal, 6-21
- Atom, 1-9
- Atomic magnets, 1-103
- Atomic structure, 5-2
- Audio frequencies, 3-75
- Audion, 3-1
- Audio transformer, 2-47
- Automatic frequency control (AFC), 4-110
- Automatic limit control (ALC), 6-91
- Automatic volume control (AVC), 4-31
- Autotransformer, 2-58
- Avalanche diode, 5-62
- Avalanche effect, 5-62
- AVC (automatic volume control), 4-31, 5-51
  - delayed AVC, 4-34
  - delayed and amplified AVC (DAVC), 4-35
- Average value, 2-15
- A-voltage, 3-12

- Back emf, 2-24
- Backwave, 6-63
- Balanced-bridge modulator, 6-101
- Balanced modulator, 4-59, 6-97, 6-100
- Ballast registor, 1-64
- Bandpass filter, 2-131, 6-102
- Bandspread tuning, 4-45
- Bandwidth, 6-72
  - adjustable, 4-46
- Barium titanate crystal, 6-82
- Base, 2-3, 5-12
- Basic cell, 1-40
- Basic transistor circuits, 5-24
- Basing, tube, 3-28
- Bass control, 4-29
- Battery, 1-33, 1-39, 1-40, 1-51
  - charger, 1-45
  - eliminator, 5-57
  - symbol, 1-51
- Beam antenna, 6-148
- Beam-power tube, 3-25
- Beat frequencies, 4-19
- Beat frequency oscillator (BFO), 4-47
- Beta, 5-28
- BFO (beat frequency oscillator), 4-47
- Bias, 3-12
  - fixed, 3-73
  - grid, 3-63
  - grid-leak, 3-74, 3-115, 4-85
  - oscillator, 3-115
  - self-, 3-73, 3-74
  - voltages, 6-58
- Bipolar transistor, 5-70
- Bleeder resistor, 3-42
- Blocked-grid keying, 6-65
- Blocking capacitor, 3-81
- Bohr
  - atom, 1-10
  - Niels, 1-10
- Bound electron, 1-12
- Breakdown voltage, 5-62
- Brown and Sharpe Gage, 1-61
- B-supply, 3-7, 3-30
- BT-cut crystal, 6-21
- Bucking, 1-116
- Buffer amplifier, 6-37
- Bunching grid, 3-128
- Butler overtone oscillator, 6-27
- Buzz control, 4-106
- B-voltage, 3-12
- Bypassing, 3-90

- Calorimeter, 6-60
- Capacitance, 2-61
  - interelectrode, 3-69
  - parallel, 2-80
  - series, 2-81
  - unit of, 2-70
- Capacitative a-c circuit, 2-92
- Capacitative reactance, 2-82, 2-83
- Capacitor(s), 1-27, 5-76
  - action with a-c, 2-68
  - bathtub, 2-73
  - blocking, 3-81
  - ceramic, 2-74
  - charging, 2-62
  - color-code, 2-76
  - coupling, 3-81, 6-43
  - disc, 2-74
  - discharging, 2-67
  - electric field, 2-66
  - electrolytic, 2-78
  - filter, 3-37
  - fixed, 2-73
  - glass, 2-75
  - -input filter, 3-40
- Capacitor(s) *(continued)*
  - metallized, 2-73
  - mica, 2-74
  - padder, 4-21
  - paper, 2-73
  - in parallel, 2-80
  - phase shift in, 2-69
  - plastic, 2-75
  - in series, 2-81
  - split stator, 6-53
  - tantalum, 2-79
  - temperature coefficient, 2-76
  - tubular, 2-73
  - variable, 2-77, 4-11
  - working voltage, 2-73
- Carbon
  - atom, 1-10
  - microphone, 3-107, 6-82
- Carborundum crystal, 4-7
- Carrier(s)
  - current, 5-5
  - envelope, 4-63
  - majority, 5-10
  - minority, 5-10
  - suppression, 6-100
  - wave, 3-129
- Cascaded amplifier, 3-75, 3-90
- Cascode r-f amplifier, 4-78
- Cat whisker, 4-7, 5-1, 5-11
- Catcher grid, 3-128
- Cathode, 3-3
  - bias, 3-73
  - emitter, 6-4
  - follower, 3-89
  - keying, 6-64
  - virtual, 3-25
- CCS ratings, 6-8
- Cell, 1-33, 1-40
  - fuel, 1-47
  - Le Clanche, 1-41
  - lead-acid, 1-44
  - mercury, 1-43, 5-57
  - nickel-cadmium, 1-46, 5-57
  - primary, 1-40—1-43
  - secondary, 1-44—1-46
  - solar, 1-48
  - storage, 1-44
  - symbol, 1-51
  - zinc carbon, 1-41, 5-57
  - zinc-mercury oxide, 1-43
- Centertap, 2-54
- Centrifugal force, 1-11
- Ceramic microphone, 6-82
- Ceramic tubes, 6-7
- Characteristic curves, 5-33
- Characteristic impedance, 6-120, 6-121
- Charged surfaces, 1-14
- Charges, electrical, 1-3, 1-5, 1-14
- Charging
  - current, 2-64
  - voltage, 2-64
- Chemical effect, 1-38
- Chirp, 6-63
- Choke coil, 3-39

Choke-input filter, 3-41
Choke modulation, 6-76
Circle, analysis of, 2-2
Circuit(s), 1-54, 1-74
  capacitative, 2-92
  closed, 1-55
  common base, 5-24
  common collector, 5-24
  common emitter, 5-24
  converter, 4-79
  crystal, 6-24
  current, 1-57
  diagrams, 5-22
  grounded base, 5-24
  grounded collector, 5-24
  grounded emitter, 5-24
  heater, 3-50
  hybrid integrated, 5-71
  inductive, 2-34
  input, 6-50
  integrated, 5-71—5-76
  limiter, 4-70, 4-84
  mixer, 4-79
  mixer-oscillator, 5-47
  mixing, 4-23
  monolithic, 5-71
  multiplex stereo FM, 4-124
  non-linear mixing, 6-69
  notch, 4-51
  null, 4-51
  open, 1-54
  output, 6-55
  overload relay, 6-113
  parallel. *See* Parallel circuits
  phase-modulation, 6-97
  R-C, 2-86
  resistive a-c, 2-92
  resonant, 2-112
  r-f amplifier, 4-77
  series. *See* Series circuits
  shunt, 1-88
  squelch, 4-55
  tank, 2-124
  transistor, 5-24
  triode, 3-14
  tuned, 4-9
  UJT-controlled relay, 5-66
  See also Class-C amplifier
Circular mil, 1-61
Circulating current, 2-123
Circumference, 2-2
Citizens Band receiver, 4-56
Citizens Band transceiver, 6-116
Clapp oscillator, 6-16, 6-17
Class-A amplifier, 3-70, 3-99
Class-AB amplifier, 3-72
Class-B amplifier, 3-71, 3-100
  linear, 6-106
Class-C amplifier, 3-72, 6-31
  grid circuit, 6-34
  plate circuit, 6-35
  transistor, 6-36
  tuned r-f, 6-34
Closed circuit, 1-55
Coaxial cable, 4-76, 6-119
Coil, 1-111
  voice, 3-101, 3-105
Cold-cathode emission, 3-3
Collector, 5-12
  neutralization, 5-49
  voltage-current characteristics, 5-17
Color code for resistors, 1-63
Colpitts oscillator, 3-120, 5-45, 6-16
Common base amplifier, 5-25
Common base circuit, 5-24
Common collector amplifier, 5-29
Common collector circuit, 5-24
Common emitter amplifier, 5-27
Common emitter circuit, 5-24
Communications receivers, 4-42
Commutator, 1-117
Complementary symmetry push-pull amplifier, 5-56
Complex wave, 2-14
Components, 5-74
Compounds, 1-8
Compressional crystal mode, 6-22
Condenser, 1-27, 2-61
Conductance, 1-30
Conductors, 1-30
Contact charging, 1-15
Continuous wave. *See* CW
Control grid, 3-12, 6-5
  modulation, 6-78
  ratings, 6-5
Control tube, 3-54
Converter, 4-24, 5-48
  circuit, 4-79
  pentagrid, 4-24
Copper, 1-30
  atom, 1-10
  losses, 2-57
  oxide rectifier, 2-132
Core saturation, 2-27
Cosine, 2-3
Coulomb, 1-36
  Charles, 1-36
Counter emf, 2-24
Coupling, 3-75, 3-111, 6-43
  capacitor, 3-81, 6-43
  coefficient, 2-30
  direct, 3-87, 5-38
  inductive, 2-29
  interstage, 5-37
  link, 6-43
  output, 6-56, 6-57
  R-C, 3-81
  transformer, 3-86, 3-110, 5-37
  of transmission lines, 6-56
Covalent bond, 5-3
Cross-neutralization, 6-48
Crystal(s), 1-9, 5-3
  action, 6-19
  AT-cut, 6-21
  axes, 6-20
  barium titanate, 6-82
  basic oscillator, 6-25
  BT-cut, 6-21
Crystal(s) *(continued)*
  Butler overtone, 6-27
  characteristics, 6-24
  circuit, 6-24
  compressional mode, 6-22
  cuts, 6-20
  detector, 4-7
  filters, 4-46, 6-103, 6-104
  flexure mode, 6-22
  fundamental frequency, 6-22
  galena, 4-7, 5-11
  harmonis, 6-22
  holder, 6-23
  lattice filter, 6-104
  longitudinal mode, 6-22
  microphone, 3-108, 6-82
  oven, 6-23
  overtone oscillator, 6-27
  quartz, 6-19
  receiver, 4-7
  rochelle salt, 6-19
  shear mode, 6-22
  temperature coefficient, 6-21
  tourmaline, 6-19
  wafer, 6-20
  X-cut, 6-20
  Y-cut, 6-20
Current, 1-28, 1-51
  amplification factor, 3-19, 5-18
  capacity, 1-50, 1-51
  carriers, 5-5
  distribution. *See* Current distribution
  discharge, 2-65, 2-67
  feedback, 3-104
  flow, 2-110, 2-122
  gain, 5-34
  grid, 3-13
  leakage, 2-76
  loops, 6-126
  nodes, 6-126
  Ohm's Law for, 1-66
  peak plate, 3-34
  plate, 3-7
Current distribution
  in parallel L-C circuit, 2-114
  in parallel L-C-R circuit, 2-118
  in parallel R-L circuit, 2-43
  in parallel resonant L-C circuit, 2-122
  in series L-C circuit, 2-102
  in series R-C circuit, 2-86
  in series R-L circuit, 2-40
Current-turns ratio, 2-53
Cutoff, 3-16
  frequency, 5-21
  projected, 3-100
  remote, 3-26
  sharp, 3-26
C-voltage, 3-12, 3-20
CW (continuous wave), 3-129, 6-3
  signal, 4-47
  transmitter, 6-45, 6-67
CW-AM transmitter, 6-92
Cycle, 2-11

Damped oscillation, 3-113, 6-12
D'Arsonval meter, 1-222, 1-223
DAVC (delayed and amplified AVC), 4-35
D-c (direct current), 1-56
D-c motor, 1-117
D-c plate resistance, 3-9, 3-20
D-c to d-c converter, 6-111
Dead-man's stick, 6-109
Decibel, 3-77
Decoupling, 3-90, 5-37
De-emphasis, 4-116
De Forest, Lee, 3-1
Degeneration, 5-32, 5-40
Degenerative feedback, 3-104
Delayed and amplified AVC (DAVC), 4-35
Delayed AVC, 4-34
Delta, 3-10
  match, 6-156
Demodulation, 3-130
Demodulator(s), 4-28
  See also Detector(s)
Depletion region, 5-68
Depolarizer, 1-41
Detector(s), 4-28
  diode, 3-131
  first, 4-22
  FM slope, 4-87
  gated-beam FM, 4-107
  grid-leak, 3-133
  infinite-impedance, 3-134
  linearity, 3-131
  plate, 3-134
  ratio, 4-97
  second, 4-28
Deviation ratio, 4-69
Diameter, 2-2
Dielectric, 1-31, 2-61
  constant, 2-72
Difference frequency, 4-19
Difference potential, 1-26
Differential amplifier, 4-53, 5-72
Diffusion, 5-74
Diode(s), 1-32, 2-132, 3-5
  avalanche, 5-62
  characteristics, 3-11
  detector, 3-131, 4-28, 5-51
  four layer PNPN, 5-64
  gas-filled rectifier, 6-9
  junction, 2-132, 5-7
  mercury-vapor rectifier, 6-9
  point-contact, 5-11
  snap, 6-41
  snap-off, 6-41
  stabilization, 5-36
  step-recovery, 6-41
  tunnel, 5-63
  varactor, 4-113
  xenon-filled rectifier, 6-9
  zener, 3-53, 5-62
Dipole, 6-141
Direct coupling, 3-87, 5-38
Direct current (d-c), 1-56
Direct FM, 6-94
Direct waves, 6-136, 6-137
Directivity pattern, 6-147
Director element, 6-148
Discharge current, 2-65, 2-67
Discharging, 1-18—1-20
Discriminator, 4-87—4-90
  double-tuned, 4-88
  Foster-Seeley, 4-90
Distortion, 3-65, 3-76, 3-98
  phase, 3-76
Donor, 5-4
Doping, 5-4
Double-ended output stage, 5-55
Double sideband (DSB) signal, 4-59, 6-101
Doublet, 6-141
Double-tuned discriminator, 4-88
Driven element, 6-148
Driver stage, 6-45
Driving power, 6-5
Dry cell, 1-41
DSB (double sideband) signal, 4-59, 6-101
Dual conversion, 4-43
Dufay, Charles, 1-4
Dummy load, 6-60
Duo-diode, 3-5
Dynamic characteristics, 3-11, 3-57
Dynamic curves, 3-8
Dynamic microphone, 3-108, 6-83
Dynamic speaker, 3-106
Dynamic transfer characteristics, 3-61
  curve, 5-34

Earphone jack, 5-53, 5-54
Eddy currents, 2-57
Edgewise meter, 1-123
Edison, Thomas A., 3-1
Edison effect, 3-1
Effective resistance, 2-112
Effective value, 2-16
Electric current, 1-28, 1-36
Electric fields, 1-21, 2-66, 6-133
Electric lines of force, 6-135
Electrical energy storage, 1-27
Electrical equilibrium, 1-11
Electrical force, 1-11
Electrical horsepower, 1-70
Electrical power, 1-70
Electrical symbols, 1-74
Electrical wavelength, 6-125
Electricity, 1-7
  discovery of, 1-2
  static, 1-27
Electrode(s), 1-40, 3-2
Electrodynanometer wattmeter, 1-136
Electrolyte, 1-40, 1-44, 2-78
Electromagnet, 1-111, 1-114
Electromagnetism, 1-99, 1-109, 6-133, 6-134
Electromotive force (emf), 1-33
Electron-coupled oscillator, 3-122
Electron(s), 1-2, 1-7
  bound, 1-12
  drift, 1-28, 1-37
  free, 1-13—1-34
  pair-bond, 5-3
  planetary, 1-10, 1-11
  tube. *See* Tube
  velocity, 1-37
Electrostatic(s), 1-27
  field, 3-13
Elements, chemical, 1-8, 1-10
  See also Individual elements
Emf (electromotive force), 1-33
Emission
  cold-cathode, 3-3
  electron, 3-3
  photoelectric, 3-3
  secondary, 3-3, 3-23
  thermionic, 3-3, 3-4
Emitter, 5-12, 6-4
Emitter-follower, 5-29
Etch, 5-74, 5-76
Even-order harmonics, 6-40
Exponential curve, 2-94
External anode, 6-7

Farad, 2-70
Faraday, Michael, 1-22, 1-105, 2-70
Family of curves
  grid characteristic curves, 3-17
  plate characteristic curves, 3-18
Feedback, 3-69, 3-103
  tickler, 3-116
  voltage, 3-104
Feedpoint impedance, 6-146
Ferri-loopstick antenna, 4-36
Ferrite(s), 1-38, 2-51
Ferrite-rod antenna, 5-43
FET (Field Effect Transistor)
  depletion region, 5-68
  Insulated Gate Field Effect Transistor (IGFET), 5-69
  Metal Oxide Semiconductor Field Effect Transistor (MOSFET), 5-69
  n-channel MOSFET, 5-69
  n-type JFET, 5-67
  p-channel MOSFET, 5-70
  p-type JFET, 5-68
  pinch-off, 5-68
Fidelity, 4-4
Field coil, 1-117, 3-106
Field Effect Transistor. *See* FET
Filament, 3-3, 3-4
Filter(s), 3-30
  bandpass, 2-131, 6-102
  band-reject, 2-131
  choke, 3-39
  fundamentals, 2-129
  high-pass, 2-130
  low-pass, 2-130
  mechanical, 4-48

Filter(s) *(continued)*
  pi, 3-40
  R-C, 3-42
Final amplifier, 6-45
First detector, 4-22
Fixed bias, 3-73
Fleming, J. A., 3-1
Flexure crystal mode, 6-22
Flux density, 1-106
FM (frequency modulation), 4-64
  antenna, 4-74
  buzz control, 4-106
  de-emphasis, 4-116
  deviation ratio, 4-69
  direct, 6-94
  discriminator, 4-87—4-90
  fundamentals of, 4-64
  gated-beam FM detector, 4-107
  grid-leak bias limiting, 4-85
  guardband, 4-67
  indirect, 6-96
  limiter circuit, 4-70
  limiting, 4-83
  modulation index, 4-69
  multiplex stereo FM, 4-117, 4-124
  noise, 4-70
  plate circuit limiter, 4-84
  pre-emphasis, 4-71
  ratio detector, 4-97
  receivers, 4-70
  SCA (Subsidiary Communications Authorization), 4-118
  sidebands, 4-67
  slope detector, 4-87
  stereophonic, 4-113
  stereo reception, 4-120
  subcarrier, 4-117
  transmitter, 4-72
  tuner, 4-114, 5-43
Folded dipole antenna, 4-75, 6-150
Forward-biased junction, 5-9
Forward breakover voltage, 5-64
Foster-Seeley discriminator, 4-90
Four-layer (PNPN) diode, 5-64
Franklin, Benjamin, 1-4
Free electron, 1-13—1-34
Free-space wave, 6-134
Frequency, 2-12, 6-134
  allocation, 4-2
  audio, 3-75
  beat, 4-19
  cutoff, 5-21
  difference, 4-19
  distortion, 3-76
  doubler, 6-39, 6-41
  fundamental, 6-22, 6-35
  modulation. *See* FM
  multiplier, 6-38, 6-39, 6-42
  quadrupler, 6-39
  resonant, 2-108, 2-121
  response, 3-79, 5-21
  ripple, 3-34
  spectrum, 4-2

Frequency *(continued)*
  tripler, 6-39, 6-41
  ultra-high (UHF), 4-2
  very high (VHF), 4-2
  very low (VLF), 4-2
Fuel cell, 1-47
Full-wave rectifier, 3-35
Full-wave voltage doubler, 3-48
Fundamental antenna, 6-141
Fundamental frequency, 6-22, 6-35
Fuse, 1-38, 1-97
Fusible resistor, 3-46

Gain, 3-66, 3-84
Galena crystal, 4-7, 5-11
Gas-filled rectifier diode, 6-9
Gas tube, 3-51
Gated-beam FM detector, 4-107
Gauss, 1-105
Generating a-c, 2-8
Generation of emf, 1-39
Generator, 1-39, 1-118
Germanium, 1-32, 5-2, 5-3
Getter, 3-2
Gilbert, William, 1-2
Grid, 3-12
  bias, 3-63, 6-78
  bunching, 3-128
  characteristic curves, 3-17
  current, 3-13
  drive, 6-34
  limiter, 4-105, 4-106
  neutralization, 6-47
  quadrature, 4-105
  screen, 3-22
  suppressor, 3-24
  tank, 6-34, 6-51
Grid-leak
  bias, 3-74, 3-115, 4-85
  detector, 3-133
Grounded base circuit, 5-24
Grounded collector circuit, 5-24
Grounded emitter circuit, 5-24
Grounded-grid amplifier, 3-88
Grounded-plate amplifier, 3-89
Ground plane antenna, 6-152
Ground-reflected waves, 6-137
Ground waves, 6-136, 6-137
Guardband, 4-67

Half-wave dipole antenna, 4-74, 6-141
  current distribution, 6-144
  directivity, 6-147
  resonance, 6-143
  voltage distribution, 6-144
Half-wave doublet, 6-141
Half-wavelength dimension, 6-142
Half-wave rectifier, 3-34
Half-wave voltage doubler, 3-43
Harmonic(s), 6-22, 6-40
  frequencies, 6-35
  generator, 6-41

Hartley oscillator, 3-117, 5-44, 6-15
  series-fed, 6-15
  shunt-fed, 6-15
  transistorized, 6-17
Heat effect, 1-38
Heater, 3-4
  circuit, 3-50
Heat sinks, 5-35
Heising modulation, 6-76
Henry, 2-27
Heptode, 3-27
Hertz, 2-12
Heterodyne, 4-17
Heterodyning, 4-19
High frequency (HF), 4-2
  oscillator, 3-121
High-mu, 3-19
High-Q, 2-112
Hole, 5-5, 5-6
Horizontal polarization, 6-133
Hosepower, 1-70
Hybrid integrated circuit, 5-71
Hydrogen, 1-9
  atom, 1-10
Hydrometer, 1-44
Hypotenuse, 2-3
Hysteresis, 2-57

IC(s), 1-32
  capacitor, 5-76
  components, 5-74
  construction, 5-74
  differential amplifier, 5-72
  diffusion, 5-74
  etch, 5-74, 5-76
  hybrid circuit, 5-71
  linear amplifier, 5-72, 5-73
  mask, 5-74
  metallic interconnection, 5-74
  monolithic circuit, 5-71
  multi-purpose linear amplifier, 5-73
  photo-resist, 5-74
  resistors, 5-76
  silicon dioxide, 5-74
  substrate, 5-71
  thick film, 5-71
  thin film, 5-71, 5-76
ICAS ratings, 6-8
IF (intermediate frequency), 4-17, 4-19, 4-22
  amplifier, 4-26, 4-27, 4-81, 5-49
  bandpass, 4-82
IGFET (Insulated Gate Field Effect Transistor), 5-69
Image frequency, 4-25
Impedance, 2-36
  in antennas, 6-145
  calculation of, 2-101, 2-104
  characteristic, 6-120, 6-121
  coupling, 3-85, 3-110, 5-38
  feedpoint, 6-146
  graphical determination of 2-38

Damped oscillation, 3-113, 6-12
D'Arsonval meter, 1-222, 1-223
DAVC (delayed and amplified AVC), 4-35
D-c (direct current), 1-56
D-c motor, 1-117
D-c plate resistance, 3-9, 3-20
D-c to d-c converter, 6-111
Dead-man's stick, 6-109
Decibel, 3-77
Decoupling, 3-90, 5-37
De-emphasis, 4-116
De Forest, Lee, 3-1
Degeneration, 5-32, 5-40
Degenerative feedback, 3-104
Delayed and amplified AVC (DAVC), 4-35
Delayed AVC, 4-34
Delta, 3-10
  match, 6-156
Demodulation, 3-130
Demodulator(s), 4-28
  See also Detector(s)
Depletion region, 5-68
Depolarizer, 1-41
Detector(s), 4-28
  diode, 3-131
  first, 4-22
  FM slope, 4-87
  gated-beam FM, 4-107
  grid-leak, 3-133
  infinite-impedance, 3-134
  linearity, 3-131
  plate, 3-134
  ratio, 4-97
  second, 4-28
Deviation ratio, 4-69
Diameter, 2-2
Dielectric, 1-31, 2-61
  constant, 2-72
Difference frequency, 4-19
Difference potential, 1-26
Differential amplifier, 4-53, 5-72
Diffusion, 5-74
Diode(s), 1-32, 2-132, 3-5
  avalanche, 5-62
  characteristics, 3-11
  detector, 3-131, 4-28, 5-51
  four layer PNPN, 5-64
  gas-filled rectifier, 6-9
  junction, 2-132, 5-7
  mercury-vapor rectifier, 6-9
  point-contact, 5-11
  snap, 6-41
  snap-off, 6-41
  stabilization, 5-36
  step-recovery, 6-41
  tunnel, 5-63
  varactor, 4-113
  xenon-filled rectifier, 6-9
  zener, 3-53, 5-62
Dipole, 6-141
Direct coupling, 3-87, 5-38
Direct current (d-c), 1-56
Direct FM, 6-94
Direct waves, 6-136, 6-137
Directivity pattern, 6-147
Director element, 6-148
Discharge current, 2-65, 2-67
Discharging, 1-18—1-20
Discriminator, 4-87—4-90
  double-tuned, 4-88
  Foster-Seeley, 4-90
Distortion, 3-65, 3-76, 3-98
  phase, 3-76
Donor, 5-4
Doping, 5-4
Double-ended output stage, 5-55
Double sideband (DSB) signal, 4-59, 6-101
Doublet, 6-141
Double-tuned discriminator, 4-88
Driven element, 6-148
Driver stage, 6-45
Driving power, 6-5
Dry cell, 1-41
DSB (double sideband) signal, 4-59, 6-101
Dual conversion, 4-43
Dufay, Charles, 1-4
Dummy load, 6-60
Duo-diode, 3-5
Dynamic characteristics, 3-11, 3-57
Dynamic curves, 3-8
Dynamic microphone, 3-108, 6-83
Dynamic speaker, 3-106
Dynamic transfer characteristics, 3-61
  curve, 5-34

Earphone jack, 5-53, 5-54
Eddy currents, 2-57
Edgewise meter, 1-123
Edison, Thomas A., 3-1
Edison effect, 3-1
Effective resistance, 2-112
Effective value, 2-16
Electric current, 1-28, 1-36
Electric fields, 1-21, 2-66, 6-133
Electric lines of force, 6-135
Electrical energy storage, 1-27
Electrical equilibrium, 1-11
Electrical force, 1-11
Electrical horsepower, 1-70
Electrical power, 1-70
Electrical symbols, 1-74
Electrical wavelength, 6-125
Electricity, 1-7
  discovery of, 1-2
  static, 1-27
Electrode(s), 1-40, 3-2
Electrodynanometer wattmeter, 1-136
Electrolyte, 1-40, 1-44, 2-78
Electromagnet, 1-111, 1-114
Electromagnetism, 1-99, 1-109, 6-133, 6-134
Electromotive force (emf), 1-33
Electron-coupled oscillator, 3-122
Electron(s), 1-2, 1-7
  bound, 1-12
  drift, 1-28, 1-37
  free, 1-13—1-34
  pair-bond, 5-3
  planetary, 1-10, 1-11
  tube. *See* Tube
  velocity, 1-37
Electrostatic(s), 1-27
  field, 3-13
Elements, chemical, 1-8, 1-10
  See also individual elements
Emf (electromotive force), 1-33
Emission
  cold-cathode, 3-3
  electron, 3-3
  photoelectric, 3-3
  secondary, 3-3, 3-23
  thermionic, 3-3, 3-4
Emitter, 5-12, 6-4
Emitter-follower, 5-29
Etch, 5-74, 5-76
Even-order harmonics, 6-40
Exponential curve, 2-94
External anode, 6-7

Farad, 2-70
Faraday, Michael, 1-22, 1-105, 2-70
Family of curves
  grid characteristic curves, 3-17
  plate characteristic curves, 3-18
Feedback, 3-69, 3-103
  tickler, 3-116
  voltage, 3-104
Feedpoint impedance, 6-146
Ferri-loopstick antenna, 4-36
Ferrite(s), 1-38, 2-51
Ferrite-rod antenna, 5-43
FET (Field Effect Transistor)
  depletion region, 5-68
  Insulated Gate Field Effect Transistor (IGFET), 5-69
  Metal Oxide Semiconductor Field Effect Transistor (MOSFET), 5-69
  n-channel MOSFET, 5-69
  n-type JFET, 5-67
  p-channel MOSFET, 5-70
  p-type JFET, 5-68
  pinch-off, 5-68
Fidelity, 4-4
Field coil, 1-117, 3-106
Field Effect Transistor. *See* FET
Filament, 3-3, 3-4
Filter(s), 3-30
  bandpass, 2-131, 6-102
  band-reject, 2-131
  choke, 3-39
  fundamentals, 2-129
  high-pass, 2-130
  low-pass, 2-130
  mechanical, 4-48

- Filter(s) *(continued)*
  - pi, 3-40
  - R-C, 3-42
- Final amplifier, 6-45
- First detector, 4-22
- Fixed bias, 3-73
- Fleming, J. A., 3-1
- Flexure crystal mode, 6-22
- Flux density, 1-106
- FM (frequency modulation), 4-64
  - antenna, 4-74
  - buzz control, 4-106
  - de-emphasis, 4-116
  - deviation ratio, 4-69
  - direct, 6-94
  - discriminator, 4-87—4-90
  - fundamentals of, 4-64
  - gated-beam FM detector, 4-107
  - grid-leak bias limiting, 4-85
  - guardband, 4-67
  - indirect, 6-96
  - limiter circuit, 4-70
  - limiting, 4-83
  - modulation index, 4-69
  - multiplex stereo FM, 4-117, 4-124
  - noise, 4-70
  - plate circuit limiter, 4-84
  - pre-emphasis, 4-71
  - ratio detector, 4-97
  - receivers, 4-70
  - SCA (Subsidiary Communications Authorization), 4-118
  - sidebands, 4-67
  - slope detector, 4-87
  - stereophonic, 4-113
  - stereo reception, 4-120
  - subcarrier, 4-117
  - transmitter, 4-72
  - tuner, 4-114, 5-43
- Folded dipole antenna, 4-75, 6-150
- Forward-biased junction, 5-9
- Forward breakover voltage, 5-64
- Foster-Seeley discriminator, 4-90
- Four-layer (PNPN) diode, 5-64
- Franklin, Benjamin, 1-4
- Free electron, 1-13—1-34
- Free-space wave, 6-134
- Frequency, 2-12, 6-134
  - allocation, 4-2
  - audio, 3-75
  - beat, 4-19
  - cutoff, 5-21
  - difference, 4-19
  - distortion, 3-76
  - doubler, 6-39, 6-41
  - fundamental, 6-22, 6-35
  - modulation. *See* FM
  - multiplier, 6-38, 6-39, 6-42
  - quadrupler, 6-39
  - resonant, 2-108, 2-121
  - response, 3-79, 5-21
  - ripple, 3-34
  - spectrum, 4-2
- Frequency *(continued)*
  - tripler, 6-39, 6-41
  - ultra-high (UHF), 4-2
  - very high (VHF), 4-2
  - very low (VLF), 4-2
- Fuel cell, 1-47
- Full-wave rectifier, 3-35
- Full-wave voltage doubler, 3-48
- Fundamental antenna, 6-141
- Fundamental frequency, 6-22, 6-35
- Fuse, 1-38, 1-97
- Fusible resistor, 3-46

- Gain, 3-66, 3-84
- Galena crystal, 4-7, 5-11
- Gas-filled rectifier diode, 6-9
- Gas tube, 3-51
- Gated-beam FM detector, 4-107
- Gauss, 1-105
- Generating a-c, 2-8
- Generation of emf, 1-39
- Generator, 1-39, 1-118
- Germanium, 1-32, 5-2, 5-3
- Getter, 3-2
- Gilbert, William, 1-2
- Grid, 3-12
  - bias, 3-63, 6-78
  - bunching, 3-128
  - characteristic curves, 3-17
  - current, 3-13
  - drive, 6-34
  - limiter, 4-105, 4-106
  - neutralization, 6-47
  - quadrature, 4-105
  - screen, 3-22
  - suppressor, 3-24
  - tank, 6-34, 6-51
- Grid-leak
  - bias, 3-74, 3-115, 4-85
  - detector, 3-133
- Grounded base circuit, 5-24
- Grounded collector circuit, 5-24
- Grounded emitter circuit, 5-24
- Grounded-grid amplifier, 3-88
- Grounded-plate amplifier, 3-89
- Ground plane antenna, 6-152
- Ground-reflected waves, 6-137
- Ground waves, 6-136, 6-137
- Guardband, 4-67

- Half-wave dipole antenna, 4-74, 6-141
  - current distribution, 6-144
  - directivity, 6-147
  - resonance, 6-143
  - voltage distribution, 6-144
- Half-wave doublet, 6-141
- Half-wavelength dimension, 6-142
- Half-wave rectifier, 3-34
- Half-wave voltage doubler, 3-43
- Harmonic(s), 6-22, 6-40
  - frequencies, 6-35
  - generator, 6-41
- Hartley oscillator, 3-117, 5-44, 6-15
  - series-fed, 6-15
  - shunt-fed, 6-15
  - transistorized, 6-17
- Heat effect, 1-38
- Heater, 3-4
  - circuit, 3-50
- Heat sinks, 5-35
- Heising modulation, 6-76
- Henry, 2-27
- Heptode, 3-27
- Hertz, 2-12
- Heterodyne, 4-17
- Heterodyning, 4-19
- High frequency (HF), 4-2
  - oscillator, 3-121
- High-mu, 3-19
- High-Q, 2-112
- Hole, 5-5, 5-6
- Horizontal polarization, 6-133
- Hosepower, 1-70
- Hybrid integrated circuit, 5-71
- Hydrogen, 1-9
  - atom, 1-10
- Hydrometer, 1-44
- Hypotenuse, 2-3
- Hysteresis, 2-57

- IC(s), 1-32
  - capacitor, 5-76
  - components, 5-74
  - construction, 5-74
  - differential amplifier, 5-72
  - diffusion, 5-74
  - etch, 5-74, 5-76
  - hybrid circuit, 5-71
  - linear amplifier, 5-72, 5-73
  - mask, 5-74
  - metallic interconnection, 5-74
  - monolithic circuit, 5-71
  - multi-purpose linear amplifier, 5-73
  - photo-resist, 5-74
  - resistors, 5-76
  - silicon dioxide, 5-74
  - substrate, 5-71
  - thick film, 5-71
  - thin film, 5-71, 5-76
- ICAS ratings, 6-8
- IF (intermediate frequency), 4-17, 4-19, 4-22
  - amplifier, 4-26, 4-27, 4-81, 5-49
  - bandpass, 4-82
- IGFET (Insulated Gate Field Effect Transistor), 5-69
- Image frequency, 4-25
- Impedance, 2-36
  - in antennas, 6-145
  - calculation of, 2-101, 2-104
  - characteristic, 6-120, 6-121
  - coupling, 3-85, 3-110, 5-38
  - feedpoint, 6-146
  - graphical determination of 2-38

Damped oscillation, 3-113, 6-12
D'Arsonval meter, 1-222, 1-223
DAVC (delayed and amplified AVC), 4-35
D-c (direct current), 1-56
D-c motor, 1-117
D-c plate resistance, 3-9, 3-20
D-c to d-c converter, 6-111
Dead-man's stick, 6-109
Decibel, 3-77
Decoupling, 3-90, 5-37
De-emphasis, 4-116
De Forest, Lee, 3-1
Degeneration, 5-32, 5-40
Degenerative feedback, 3-104
Delayed and amplified AVC (DAVC), 4-35
Delayed AVC, 4-34
Delta, 3-10
  match, 6-156
Demodulation, 3-130
Demodulator(s), 4-28
  See also Detector(s)
Depletion region, 5-68
Depolarizer, 1-41
Detector(s), 4-28
  diode, 3-131
  first, 4-22
  FM slope, 4-87
  gated-beam FM, 4-107
  grid-leak, 3-133
  infinite-impedance, 3-134
  linearity, 3-131
  plate, 3-134
  ratio, 4-97
  second, 4-28
Deviation ratio, 4-69
Diameter, 2-2
Dielectric, 1-31, 2-61
  constant, 2-72
Difference frequency, 4-19
Difference potential, 1-26
Differential amplifier, 4-53, 5-72
Diffusion, 5-74
Diode(s), 1-32, 2-132, 3-5
  avalanche, 5-62
  characteristics, 3-11
  detector, 3-131, 4-28, 5-51
  four layer PNPN, 5-64
  gas-filled rectifier, 6-9
  junction, 2-132, 5-7
  mercury-vapor rectifier, 6-9
  point-contact, 5-11
  snap, 6-41
  snap-off, 6-41
  stabilization, 5-36
  step-recovery, 6-41
  tunnel, 5-63
  varactor, 4-113
  xenon-filled rectifier, 6-9
  zener, 3-53, 5-62
Dipole, 6-141
Direct coupling, 3-87, 5-38
Direct current (d-c), 1-56
Direct FM, 6-94
Direct waves, 6-136, 6-137
Directivity pattern, 6-147
Director element, 6-148
Discharge current, 2-65, 2-67
Discharging, 1-18—1-20
Discriminator, 4-87—4-90
  double-tuned, 4-88
  Foster-Seeley, 4-90
Distortion, 3-65, 3-76, 3-98
  phase, 3-76
Donor, 5-4
Doping, 5-4
Double-ended output stage, 5-55
Double sideband (DSB) signal, 4-59, 6-101
Doublet, 6-141
Double-tuned discriminator, 4-88
Driven element, 6-148
Driver stage, 6-45
Driving power, 6-5
Dry cell, 1-41
DSB (double sideband) signal, 4-59, 6-101
Dual conversion, 4-43
Dufay, Charles, 1-4
Dummy load, 6-60
Duo-diode, 3-5
Dynamic characteristics, 3-11, 3-57
Dynamic curves, 3-8
Dynamic microphone, 3-108, 6-83
Dynamic speaker, 3-106
Dynamic transfer characteristics, 3-61
  curve, 5-34

Earphone jack, 5-53, 5-54
Eddy currents, 2-57
Edgewise meter, 1-123
Edison, Thomas A., 3-1
Edison effect, 3-1
Effective resistance, 2-112
Effective value, 2-16
Electric current, 1-28, 1-36
Electric fields, 1-21, 2-66, 6-133
Electric lines of force, 6-135
Electrical energy storage, 1-27
Electrical equilibrium, 1-11
Electrical force, 1-11
Electrical horsepower, 1-70
Electrical power, 1-70
Electrical symbols, 1-74
Electrical wavelength, 6-125
Electricity, 1-7
  discovery of, 1-2
  static, 1-27
Electrode(s), 1-40, 3-2
Electrodynanometer wattmeter, 1-136
Electrolyte, 1-40, 1-44, 2-78
Electromagnet, 1-111, 1-114
Electromagnetism, 1-99, 1-109, 6-133, 6-134
Electromotive force (emf), 1-33
Electron-coupled oscillator, 3-122
Electron(s), 1-2, 1-7
  bound, 1-12
  drift, 1-28, 1-37
  free, 1-13—1-34
  pair-bond, 5-3
  planetary, 1-10, 1-11
  tube. *See* Tube
  velocity, 1-37
Electrostatic(s), 1-27
  field, 3-13
Elements, chemical, 1-8, 1-10
  See also Individual elements
Emf (electromotive force), 1-33
Emission
  cold-cathode, 3-3
  electron, 3-3
  photoelectric, 3-3
  secondary, 3-3, 3-23
  thermionic, 3-3, 3-4
Emitter, 5-12, 6-4
Emitter-follower, 5-29
Etch, 5-74, 5-76
Even-order harmonics, 6-40
Exponential curve, 2-94
External anode, 6-7

Farad, 2-70
Faraday, Michael, 1-22, 1-105, 2-70
Family of curves
  grid characteristic curves, 3-17
  plate characteristic curves, 3-18
Feedback, 3-69, 3-103
  tickler, 3-116
  voltage, 3-104
Feedpoint impedance, 6-146
Ferri-loopstick antenna, 4-36
Ferrite(s), 1-38, 2-51
Ferrite-rod antenna, 5-43
FET (Field Effect Transistor)
  depletion region, 5-68
  Insulated Gate Field Effect Transistor (IGFET), 5-69
  Metal Oxide Semiconductor Field Effect Transistor (MOSFET), 5-69
  n-channel MOSFET, 5-69
  n-type JFET, 5-67
  p-channel MOSFET, 5-70
  p-type JFET, 5-68
  pinch-off, 5-68
Fidelity, 4-4
Field coil, 1-117, 3-106
Field Effect Transistor. *See* FET
Filament, 3-3, 3-4
Filter(s), 3-30
  bandpass, 2-131, 6-102
  band-reject, 2-131
  choke, 3-39
  fundamentals, 2-129
  high-pass, 2-130
  low-pass, 2-130
  mechanical, 4-48

Filter(s) *(continued)*
  pi, 3-40
  R-C, 3-42
Final amplifier, 6-45
First detector, 4-22
Fixed bias, 3-73
Fleming, J. A., 3-1
Flexure crystal mode, 6-22
Flux density, 1-106
FM (frequency modulation), 4-64
  antenna, 4-74
  buzz control, 4-106
  de-emphasis, 4-116
  deviation ratio, 4-69
  direct, 6-94
  discriminator, 4-87—4-90
  fundamentals of, 4-64
  gated-beam FM detector, 4-107
  grid-leak bias limiting, 4-85
  guardband, 4-67
  indirect, 6-96
  limiter circuit, 4-70
  limiting, 4-83
  modulation index, 4-69
  multiplex stereo FM, 4-117, 4-124
  noise, 4-70
  plate circuit limiter, 4-84
  pre-emphasis, 4-71
  ratio detector, 4-97
  receivers, 4-70
  SCA (Subsidiary Communications Authorization), 4-118
  sidebands, 4-67
  slope detector, 4-87
  stereophonic, 4-113
  stereo reception, 4-120
  subcarrier, 4-117
  transmitter, 4-72
  tuner, 4-114, 5-43
Folded dipole antenna, 4-75, 6-150
Forward-biased junction, 5-9
Forward breakover voltage, 5-64
Foster-Seeley discriminator, 4-90
Four-layer (PNPN) diode, 5-64
Franklin, Benjamin, 1-4
Free electron, 1-13—1-34
Free-space wave, 6-134
Frequency, 2-12, 6-134
  allocation, 4-2
  audio, 3-75
  beat, 4-19
  cutoff, 5-21
  difference, 4-19
  distortion, 3-76
  doubler, 6-39, 6-41
  fundamental, 6-22, 6-35
  modulation. *See* FM
  multiplier, 6-38, 6-39, 6-42
  quadrupler, 6-39
  resonant, 2-108, 2-121
  response, 3-79, 5-21
  ripple, 3-34
  spectrum, 4-2

Frequency *(continued)*
  tripler, 6-39, 6-41
  ultra-high (UHF), 4-2
  very high (VHF), 4-2
  very low (VLF), 4-2
Fuel cell, 1-47
Full-wave rectifier, 3-35
Full-wave voltage doubler, 3-48
Fundamental antenna, 6-141
Fundamental frequency, 6-22, 6-35
Fuse, 1-38, 1-97
Fusible resistor, 3-46

Gain, 3-66, 3-84
Galena crystal, 4-7, 5-11
Gas-filled rectifier diode, 6-9
Gas tube, 3-51
Gated-beam FM detector, 4-107
Gauss, 1-105
Generating a-c, 2-8
Generation of emf, 1-39
Generator, 1-39, 1-118
Germanium, 1-32, 5-2, 5-3
Getter, 3-2
Gilbert, William, 1-2
Grid, 3-12
  bias, 3-63, 6-78
  bunching, 3-128
  characteristic curves, 3-17
  current, 3-13
  drive, 6-34
  limiter, 4-105, 4-106
  neutralization, 6-47
  quadrature, 4-105
  screen, 3-22
  suppressor, 3-24
  tank, 6-34, 6-51
Grid-leak
  bias, 3-74, 3-115, 4-85
  detector, 3-133
Grounded base circuit, 5-24
Grounded collector circuit, 5-24
Grounded emitter circuit, 5-24
Grounded-grid amplifier, 3-88
Grounded-plate amplifier, 3-89
Ground plane antenna, 6-152
Ground-reflected waves, 6-137
Ground waves, 6-136, 6-137
Guardband, 4-67

Half-wave dipole antenna, 4-74, 6-141
  current distribution, 6-144
  directivity, 6-147
  resonance, 6-143
  voltage distribution, 6-144
Half-wave doublet, 6-141
Half-wavelength dimension, 6-142
Half-wave rectifier, 3-34
Half-wave voltage doubler, 3-43
Harmonic(s), 6-22, 6-40
  frequencies, 6-35
  generator, 6-41

Hartley oscillator, 3-117, 5-44, 6-15
  series-fed, 6-15
  shunt-fed, 6-15
  transistorized, 6-17
Heat effect, 1-38
Heater, 3-4
  circuit, 3-50
Heat sinks, 5-35
Heising modulation, 6-76
Henry, 2-27
Heptode, 3-27
Hertz, 2-12
Heterodyne, 4-17
Heterodyning, 4-19
High frequency (HF), 4-2
  oscillator, 3-121
High-mu, 3-19
High-Q, 2-112
Hole, 5-5, 5-6
Horizontal polarization, 6-133
Hosepower, 1-70
Hybrid integrated circuit, 5-71
Hydrogen, 1-9
  atom, 1-10
Hydrometer, 1-44
Hypotenuse, 2-3
Hysteresis, 2-57

IC(s), 1-32
  capacitor, 5-76
  components, 5-74
  construction, 5-74
  differential amplifier, 5-72
  diffusion, 5-74
  etch, 5-74, 5-76
  hybrid circuit, 5-71
  linear amplifier, 5-72, 5-73
  mask, 5-74
  metallic interconnection, 5-74
  monolithic circuit, 5-71
  multi-purpose linear amplifier, 5-73
  photo-resist, 5-74
  resistors, 5-76
  silicon dioxide, 5-74
  substrate, 5-71
  thick film, 5-71
  thin film, 5-71, 5-76
ICAS ratings, 6-8
IF (intermediate frequency), 4-17, 4-19, 4-22
  amplifier, 4-26, 4-27, 4-81, 5-49
  bandpass, 4-82
IGFET (Insulated Gate Field Effect Transistor), 5-69
Image frequency, 4-25
Impedance, 2-36
  in antennas, 6-145
  calculation of, 2-101, 2-104
  characteristic, 6-120, 6-121
  coupling, 3-85, 3-110, 5-38
  feedpoint, 6-146
  graphical determination of 2-38

Impedance *(continued)*
  L-C in parallel, 2-115
  L-C in series, 2-100
  L-C-R in series, 2-104
  matching, 2-59, 3-101
  mismatch, 6-127
  R-C parallel circuit, 2-90
  R-C series circuit, 2-88
  reflected, 3-102
  at resonance, 2-109
  R-L parallel circuit, 2-44
  R-L series circuit, 2-37
  series resonant circuit, 2-109
  solving problems, 2-37
  of transmission lines, 6-120, 6-121
Indirect FM, 6-96
Indirectly heated cathode, 3-4
Indium, 5-2, 5-5
Induced emf, 1-117
Induced voltage, 2-8
Inductance, 2-25
  flux linkages, 2-25
  mutual, 2-29
  parallel, 2-31
  self, 2-25
  series, 2-31
Induction, 1-16
  mutual, 2-28
  self-, 2-23
Inductive circuit, 2-34, 2-92
Inductive coupling, 6-43
Inductive neutralization, 6-48
Inductive reactance, 2-32, 2-33
Inductor(s), 2-28
  filter, 3-39
  toroidal, 2-28
  variable, 2-28
Infinite-impedance detector, 3-134
Input circuit, 6-50
Input power, 6-46, 6-60
Insertion loss, 6-104
Instantaneous value, 2-14
Insulating material, 1-31
Insulated Gate Field Effect Transistor (IGFET), 5-69
Insulator(s), 1-31
Integrated circuits, 1-32
  See also IC(s)
Interelectrode capacitance(s), 3-69, 3-123, 4-12
Intermediate frequency. *See* IF
Internal resistance, 1-57
Interstage coupling, 5-37, 6-43
Ionizing potential, 6-10
Ionosphere, 6-139
IR drop, 1-82, 1-84
I^2R loss, 1-87
Iron, 1-30
Iron-core transformer, 2-51
Isolation transformer, 2-52

JFET (Junction Field Effect Transistor), 5-67
Junction
  forward-biased, 5-9
  reverse-biased, 5-8
Junction barrier, 5-7
Junction diode, 2-132, 5-7
  rectifier, 5-10
Junction Field Effect Transistor (JFET), 5-67

Kennely-Heaviside layer, 6-139
Key clicks, 6-63
  filter, 6-65
Keyer tube, 6-64
Keying
  backwave, 6-63
  blocked-grid, 6-65
  cathode, 6-64
  chirp, 6-63
  clicks, 6-63, 6-65
  CW, 6-63
  plate, 6-66
  relay, 6-64
  screen-grid, 6-66
  telegraphy, 6-63, 6-66
Kilohm, 1-58
Kilovolt, 1-34
Kilowatt hour, 1-73
Kinetic energy, 1-24
Kirchhoff, Gustav Robert, 1-96
Kirchhoff's Law(s), 1-96, 2-41
Klystron tube, 3-128

Lag, 2-20
Lambda, 6-124
Lattice, 1-9, 5-3
  filter, 4-60, 6-104
Lead, 2-20
Lead-acid cell, 1-44
Leakage current, 2-76, 5-35
Le Clanche cell, 1-41
Left-hand rule, 1-113, 1-119
Lenz, H. F. Emil, 2-24
Lenz's Law, 2-24
LF (low frequency), 4-2
Lighthouse oscillator, 3-124
Lighthouse tube, 3-124
Lightning, 1-19
Limiter
  circuit, 4-70
  grid, 4-105, 4-106
  noise, 4-54
Limiting, 4-83
Linear amplifier, 5-72, 5-73, 6-106
Linearity, 3-65
Lines of force, 1-22, 1-23, 6-132
Line-of-sight
  propagation, 6-138
  reception, 6-137
Link coupling, 6-43
Litz wire, 2-112, 4-10
L-network, 6-57, 6-62
Load, 1-54
  line, 3-59, 5-33
  resistance, 3-11, 3-57
Loading coil, 4-56
Loadstone, 1-99
Local oscillator, 4-21, 5-46
Longitudinal crystal mode, 6-22
Long-wire antenna, 6-153
Loop antennas, 4-36
Loudspeaker, 3-105
Lower sideband, 6-72
Low frequency (LF), 4-2
Low-mu, 3-19

Magnesia, 1-99
Magnet, 1-99
  permanent, 1-100
  temporary, 1-100
Magnetism
  attraction, 1-104
  conductivity, 1-112
  effect, 1-38
  energy, 1-105
  fields, 105, 2-22, 6-133
  flux, 1-106, 1-108
  lines of force, 1-105—1-108, 6-135
  materials, 1-101
  poles, 1-102
  repulsion, 1-104
Magnetomotive force, 1-115
Magnetostriction, 4-48
Magnetron tube, 3-126
Majority carriers, 5-10
Marconi antenna, 6-151
Mask, 5-74
Matching stub, 6-156
Mathematic fundamentals, 2-2
Matrix, 4-120
  analysis, 4-123
  operation, 4-122
Matter, 1-8
Maximum value, 2-17
Maxwell, 1-106, 1-115
Mechanical
  filter, 4-48
  force, 1-11
  horsepower, 1-70
Medium frequency, 4-2
Medium mu, 3-19
Megohm, 1-58
Mercury cell, 1-43, 5-57
Mercury-vapor rectifier diode, 6-9
Metal interconnection, 5-74
Metal Oxide Semiconductor Field Effect Transistor (MOSFET), 5-69
Metals, 1-12
Metering, 6-59
Meter(s), 1-75, 1-122
  sensitivity, 1-129
  shunt, 1-126
  taut-band, 1-124
Mho, 3-21
Microammeter, 1-127
Microampere, 1-37
Micromho, 3-21

Micro-ohm, 1-58
Microphone
  carbon, 3-107, 6-82
  ceramic, 6-82
  crystal, 3-108, 6-82
  dynamic, 3-108, 6-83
  moving-coil, 3-108, 6-83
  ribbon, 6-83
  velocity, 6-83
Microvolt, 1-34
Microwave oscillators, 3-123
Milliammeter, 1-127
Milliampere, 1-37
Milliohm, 1-58
Millivolt, 1-34
Mils, 1-61
Minority carriers, 5-10
Mixer, 4-22
  circuit, 4-79
  pentagrid, 4-23
  stage, 5-47
Mixer-oscillator circuit, 5-47
Mixing circuits, 4-23
Modulated continuous wave (MCW), 3-129
Modulation, 3-129, 4-63, 6-69, 6-74
  checking, 6-81
  choke, 6-76
  control-grid, 6-78
  envelope, 3-130, 6-69
  grid-bias, 6-78
  Heising, 6-76
  index, 4-69
  levels, 6-75
  percent, 6-70, 6-71
  phase, 6-94, 6-98
  plate, 6-76, 6-77, 6-88
  r-f amplifier, 6-74
  screen grid, 6-80
  stages, 6-88
  transformer, 6-77
Molecule, 1-9
Monolithic integrated circuit, 5-71
Monophonic, 4-117
MOSFET (Metal Oxide Semiconductor Field Effect Transistor), 5-69
Moving-coil
  microphone, 3-108, 6-83
  speaker, 3-105
Multiband operation, 4-44
Multiplex stereo FM, 4-117
  circuit, 4-124
Multiplier, 1-128
Multi-purpose linear amplifier, 5-73
Mutual conductance, 3-19, 3-21
Mutual inductance, 2-20, 2-29

N-channel MOSFET, 5-69
Negative charge, 1-15
Negative conductance region, 5-63
Negative electricity, 1-4
Negative feedback, 3-103, 5-40, 5-49
Negative ion, 1-28
Negative resistance, 3-23
Negative temperature coefficient, 1-64
Negative terminal, 1-33
Negative voltage, 3-44
Neutralization, 6-42, 6-47
Neutron, 1-10, 5-2
Nichrome, 1-30
Nickel-cadmium cell, 1-46, 5-57
Noise, 4-42
  limiter, 4-54
Non-inductive winding, 2-26
Non-linear distortion, 3-76
Non-linear mixing circuit, 6-69
Nonmagnetic materials, 1-101
Notch circuit, 4-51
N-P-N transistor, 5-12
  operation, 5-16
N-type JFET, 5-67
N-type semiconductor, 5-4
Nucleus, 1-10
Null circuit, 4-51

Odd-order harmonics, 6-40
Oersted, Hans Christian, 1-109
Ohm, 1-58
  George Simon, 1-58, 1-66
Ohmmeter, 1-75, 1-79, 1-132
  series, 1-132
  shunt, 1-133
Ohm's Law, 1-66—1-69
  for a-c, 2-39
Ohms-per-volt, 1-130
Open circuit, 1-54
Open-wire transmission line, 6-119
Operating point, 3-64, 3-70
Orbit, 1-12
Oscillation, 3-113
Oscillator(s), 3-113, 5-44, 6-11
  Armstrong, 3-116
  basic circuit, 6-13
  beat frequency, 4-47
  bias, 3-115
  Butler overtone, 6-27
  characteristics, 6-14
  Clapp, 6-16, 6-17
  Colpitts, 3-120, 5-45, 6-16
  coupling, 6-29
  crystal. *See* Crystal(s)
  electron-coupled, 3-122
  harmonics, 6-22
  Hartley, 3-117, 5-44, 6-15, 6-17
  high-frequency, 3-121
  Klystron, 3-128
  lighthouse, 3-124
  loading, 6-29
  local, 5-46
  losses, 6-12
  magnetron, 3-126
  microwave, 3-123
  phase-shift, 5-45
Oscillator(s) *(continued)*
  Pierce, 6-26
  planar, 3-124
  regenerative-feedback, 6-13
  series-fed, 3-119
  shock excitation, 6-14
  shunt-fed, 3-119
  tickler-feedback, 3-116
  transistor, 6-17
  tuned-plate tuned-grid (TPTG) 6-18
  UJT, 5-66
  ultra-high frequency, 3-123
  ultraudion, 3-121
  variable-frequency, 6-28
Output circuits, 6-55
Output coupling, 6-56, 6-57
Output power, 6-60
Output-signal power, 6-6
Output transformer, 3-101, 3-102
Output voltage, 1-49
Overload diode, 5-50
Overload relay circuit, 6-113
Overtones. *See* Harmonics

Padder capacitor, 4-21
Parallel capacitance, 2-80
Parallel circuit(s), 1-88
  branch circuit impedance, 2-115
  branch current, 2-114, 2-118, 2-127
  circulating current, 2-123
  L-C, 2-114
  L-C-R, 2-117
  line circuit impedance, 2-116, 2-119
  line current, 2-116, 2-118, 2-119, 2-128
  R-C, 2-89
  resonant impedance, 2-122
  resonant L-C, 2-121
  resonant line current, 2-122
  R-L, 2-42, 2-43
  summary of, 2-45
Parallel-connected, 1-52
Parallel inductance, 2-31
Parallelogram, 2-6
Paraphase amplifier, 3-93
Parasitic array, 6-148, 6-149
Parasitic oscillation, 6-89
P-channel MOSFET, 5-70
Peak
  current, 5-63
  inverse voltage, 3-34, 3-45, 3-38
  plate current, 3-34
  value, 2-14
  voltage, 5-63
Peak-to-peak, 2-14
Pentagrid, 3-27
  converter, 4-24
  mixer, 4-23
Pentavalence, 5-4
Pentode, 3-24
  triode-connected, 3-97

Percent modulation, 6-70, 6-71
Permanent magnet, 1-100
Permeability, 1-112
  tuning, 4-10
Phase, 2-19
  distortion, 3-76
  inverter, 3-91
  modulation, 6-94, 6-98
  relationships, 3-67
  shift, 2-48, 2-69, 2-86, 2-117
Phasing method of sideband removal, 6-105
Photoelectric emission, 3-3
Photo-resist, 5-74
Pierce oscillator, 6-26
Pie winding, 6-44
Piezoelectric, 1-39
  effect, 3-108, 6-19, 6-82
Pi filter, 3-40
Pi network, 6-53, 6-57
  tuning, 6-62
Pinch-off, 5-68
Planar tube, 3-124
Planetary electrons, 1-10, 1-11
Plate, 3-5, 6-6
  characteristic curves, 3-18
  circuit limiter, 4-84
  current, 3-7, 3-34, 3-62, 3-64, 3-70
  detector, 3-134
  efficiency, 3-70
  keying, 6-66
  modulation, 6-76, 6-77, 6-88
  neutralization, 6-47
  power input, 6-6
  resistance, 3-9, 3-10, 3-19, 3-20
  tank, 6-34, 6-55
  voltage, 3-7, 3-8
  voltage-plate current curves, 3-8
P-N-P transistor, 5-12
  operation, 5-14
Point-contact diode, 5-11
Polarity, 1-33
Polarization, 1-42
Positive charge, 1-15
Positive electricity, 1-4
Positive feedback, 3-103
Positive ion, 1-13, 1-28, 6-10
Positive terminal, 1-33
Potential energy, 1-24
Potentiometer, 1-62
Powdered iron, 2-51
Power, 1-70
  in a-c circuit, 2-92
  amplifier. *See* Power amplifier
  apparent, 2-93
  detector, 5-52
  distribution in AM wave, 6-73
  factor, 2-93
  gain, 5-20, 5-34
  input, 6-46, 6-60
  loss, 1-87
  output, 3-99, 6-60
  rating, resistors, 1-72
  sources, 5-57
Power *(continued)*
  supplies. *See* Power supplies
  transformers, 2-47, 3-31
  voltage. *See* Voltage
Power amplifier, 3-56, 3-75, 3-94, 6-45, 6-46
  bias voltages, 6-58
  grid tank circuit, 6-51
  input circuit, 6-50
  output, 3-99
  output circuit, 6-55
  push-pull, 6-54
  single-ended, 6-53
Power supplies
  a-c—d-c, 3-45
  bleeders, 3-4
  filters, 3-37—3-42
  heater circuits, 3-50
  rectification, 3-32
  rectifiers. *See* Rectifiers
Preamplifier, 5-39
Pre-emphasis, 4-71
Preselector stage, 4-18
Primary, 2-29
Primary cell, 1-40—1-43
Propagation
  angle of radiation, 6-140
  direct waves, 6-136, 6-137
  electric fields in free space, 6-133
  electric lines of force, 6-135
  electric wavelength, 6-125
  electromagnetic, 6-133, 6-134
  free-space wave, 6-134
  frequency, 6-134
  ground-reflected waves, 6-137
  ground waves, 6-136, 6-137
  horizontal polarization, 6-133
  ionosphere, 6-139
  Kennely-Heaviside layer, 6-139
  lines of force, 6-132
  line-of-sight, 6-137, 6-138
  magnetic fields in free space, 6-133
  magnetic lines of force, 6-135
  radiation, 6-132, 6-133
  radio wave, 6-133
  refraction, 6-139
  skip distance, 6-140
  sky waves, 6-136, 6-139
  temperature inversion, 6-138
  velocity, 6-134
  velocity of propagation, 6-125
  vertical polarization, 6-133
  vertical radiation, 6-136
  wavefront, 6-135
  wavelength, 6-125, 6-134
  wave propagation, 6-136
Protons, 1-7, 5-2
P-type JFET, 5-67
P-type semiconductor, 5-5
Pushbutton tuning, 4-37
Push-pull amplifier, 3-71, 3-91, 3-95, 6-52, 6-54
  complementary symmetry, 5-56
Push-pull amplifier *(continued)*
  frequency multiplier, 6-42
  input circuit, 6-52
  output stage, 5-55

Q, 2-112, 2-125, 4-9, 6-12
  multiplier, 4-50
  resonant circuit, 2-112
Quadrature grid, 4-105
Quartz crystal, 6-19
Quiescent plate current, 3-62, 3-64, 3-70

Radar, 1-1
Radiation, 6-132
  polarization, 6-133
  resistance, 6-146
Radio communication, 6-1
Radio frequency. *See* R-f
Radio receivers. *See* Receivers
Radio signals, 6-2
Radiotelegraphy, 6-3
Radio wave, 6-113
Radius, 2-2
Rate of change, 2-18
Rate-of-flow, 1-36
Ratio detector, 4-97
R-C (resistance-capacitance)
  circuit, 2-86
  coupling, 3-81, 5-37, 6-43
  filter, 3-42
Reactance
  capacitative, 2-82, 2-85
  inductive, 2-32, 2-33
  tube, 4-110, 4-111, 6-94
  variable, 4-110
Receiver(s), 4-1
  a-c—d-c superheterodyne, 4-39
  alignment, 4-40
  AM-FM superheterodyne, 5-58
  Citizens Band, 4-56
  communications, 4-42
  crystal, 4-7
  dual conversion, 4-43
  fidelity, 4-4
  FM, 4-70
  FM tuner, 4-114
  multiplex stereo FM circuit, 4-124
  selectivity, 4-3
  sensitivity, 4-4
  superheterodyne, 4-17
  TRF (tuned-radio-frequency), 4-8, 4-15
Reception, line-of-sight, 6-137
Rectification, 3-32
Rectifier, 2-132, 3-30, 3-32, 5-10
  bridge, 3-36
  full-wave, 3-35
  gas-filled, 6-9
  half-wave, 3-34
  mercury-vapor diode, 6-9
  metallic, 3-33

Rectifier *(continued)*
  selenium, 3-33
  semiconductors, 1-32, 3-33
  silicon-controlled, 1-32
  tube, 6-9
Reflected impedance, 3-102
Reflector element, 6-148
Reflex Klystron, 3-128
Refraction, 6-139
Regenerative feedback, 3-103, 6-13
Regulation, 3-37, 3-40, 3-41, 3-57
Reluctance, 1-115
Remote cutoff, 3-26
Repulsion force, 1-11
Residual magnetism, 1-121
Resistance, 1-56
  in antennas, 6-145
  d-c, 1-56
  gain, 5-18
  internal, 1-57
  Ohm's Law for, 1-69
  plate, 3-19, 3-20
  specific, 1-59
  symbol, 1-58
Resistance-capacitance. *See* R-C
Resistive a-c circuit, 2-92
Resistive effects on series resonant circuit, 2-111
Resistor(s), 1-56, 1-62, 5-76
  bleeder, 3-42
  color code, 1-63
  fusible, 3-46
  ratings, 1-63, 1-72
  wire-wound, 1-62
Resonance, 2-108, 4-9
  calculation of, 2-121
  curve, 2-110, 2-125
Resonant circuit Q, 2-112
Resonant frequency, 2-108, 2-121
Resonant transmission line, 6-128, 6-129
Reverse-biased junction, 5-8
R-f (radio-frequency)
  amplification, 3-109
  amplifier, 4-18, 4-77, 5-43, 6-74
  choke, 6-44
  coils, 4-10
  excitation, 6-5
  spectrum, 4-2
Rheostat, 1-62
Rhombic antenna, 6-155
Ribbon lead, 6-119
Ribbon microphone, 6-83
Ripple frequency, 3-34
Rochelle salt crystal, 6-19
Root mean square (RMS) value, 2-16
Running-time meter, 6-59

Sal ammoniac, 1-41
Saturation, 3-8, 3-16
SCA (Subsidiary Communications Authorization), 4-118
Scalar quantity, 2-4
Schematic representation, 1-74
Screen grid, 3-22
  keying, 6-66
  modulation, 6-80
Secondary, 2-29
  cell(s), 1-44—1-46
  emission, 3-3, 3-23
Second detector, 4-28
Selectivity, 3-109, 4-3
Selenium rectifier, 3-33
Self-bias, 3-73, 3-74
Self-induction, 2-23
Semiconductor(s), 1-32, 5-1, 5-4
  crystals, 5-3
  rectifier, 3-33
Sensitivity, 4-4
Separation control, 4-123
Series aiding, 2-31
Series capacitance, 2-81
Series circuit(s)
  L-C, 2-99, 2-102, 2-103
  L-C-R, 2-104, 2-107, 2-108, 2-111
  R-C, 2-86
  R-L, 2-40, 2-41
  string heater, 3-50
  summary of, 2-45
  voltage and current in, 2-35
Series-connected, 1-51, 1-76
Series-fed oscillator, 3-119
Series inductance, 2-31
Series noise limiter, 4-54
Series opposing, 2-31
Series-parallel connected, 1-53, 1-94
Series string heater circuit, 3-50
Sharp cutoff, 3-26
Shear mode, 6-22
SHF (super high frequency), 4-2
Shock excitation, 6-14
Shorting stick, 6-109
Shortwave bands, 3-109
Shunt
  circuit, 1-88
  ohmmeter, 1-133
Shunt-fed oscillator, 3-119
Sideband power, 6-73
Sideband removal, 4-60
Sidebands, 6-72
Sideband suppression, 6-102
Silicon, 1-32, 5-2, 5-3
Silicon-controlled rectifier (SCR), 1-32, 5-64
Silicon dioxide, 5-74
Sine wave, 2-13
  rate of change, 2-18
Single-ended output stage, 5-54
Single-ended power amplifier, 6-53
Single sideband. *See* SSB
Sinusoidal wave, 2-13
Skin effect, 2-112
Skip distance, 6-140
Sky waves, 6-136
  propagation, 6-139
Slip ring, 2-10
Slope detector, 4-87
S meters, 4-52
Snap diode, 6-41
Snap-off diode, 6-41
Solar cell, 1-48
Solenoid, 1-111
  winding, 6-44
Space charge, 3-6
Specific gravity, 1-44
Specific resistance, 1-59
Speech amplifiers, 6-84
Speech clipping and filtering, 6-90
Speed of electricity, 1-37
Speed of light, 1-37
Split stator capacitor, 6-53
Square mils, 1-61
Square wave, 2-14
Squelch circuit, 4-55
SSB (single sideband)
  balanced bridge modulator, 6-101
  balanced modulator, 6-97, 6-100
  bandpass filter, 6-102
  basics, 6-99
  carrier suppression, 6-100
  crystal filter, 6-103
  crystal lattice filter, 6-104
  insertion loss, 6-104
  lattice-type filter, 6-104
  phasing method of removal, 6-105
  reception, 4-61
  signal, 4-58
  suppressed carrier, 6-100
  suppression, 6-102
  transmitters, 6-107
  See also DSB (double sideband) signal
Stagger tuning, 4-82
Standing wave ratio (SWR), 6-127, 6-156
Standing waves, 6-127
Static
  characteristics, 3-11
  curves, 3-8, 3-16
  electricity, 1-27
Step-recovery diode, 6-41
Stereophonic, 4-113
Storage cell, 1-44
Subcarrier, 4-117
Subsidiary Communications Authorization (SCA), 4-118
Substrate, 5-69, 5-71
Superheterodyne
  alignment, 4-40
  receiver, 4-17, 4-39, 5-58
Super-high frequency (SHF), 4-2
Suppressed carrier, 6-100
Suppressor grid, 3-24
Surface barrier, 3-3
Surge impedance, 6-121
Swinging choke, 3-41

SWR (standing wave ratio), 6-127, 6-156
Symbols, 1-74

Tangent, 2-3
Tank circuit, 2-124
Tantalum, 2-79
Taut-band meter, 1-124
Telegraph key, 6-63
  "bug," 6-66
  semi-automatic, 6-66
Telegraphy, 6-63
Temperature coefficient, 2-76
  crystal, 6-21
Temperature inversion, 6-138
Temporary magnet, 1-100
Tetrode, 3-22
Thales of Miletus, 1-2
Thermal runaway, 5-35
Thermal stabilization, 5-36
Thermionic emission, 3-3, 3-4
Thermistor, 1-64, 5-36, 5-55
  stabilization of, 5-36
Thermocouple-type ammeter, 6-60
Theta (θ), 2-2
Thick film integrated circuits, 5-71
Thin film, 5-76
  integrated circuits, 5-71
Thompson, Sir J. J., 3-1
Tickler feedback, 3-116
Time constant
  R-C, 2-96
  R-L, 2-94
Tin, 1-30
Tolerance, 1-63
Tone controls, 4-29
Toroidal inductor, 2-28
Torque, 1-117
Tourmaline crystal, 6-19
TPTG (tuned-plate tuned-grid) oscillator, 6-18
Tracking, 4-21
Transceiver, 6-116
Transconductance, 3-21
Transducer, 3-105, 4-48
Transformer, 2-46
  action, 2-48
  air-core, 2-51
  application of, 2-47
  audio, 2-47
  autotransformer, 2-58
  coupling, 3-86, 3-110, 5-37, 6-43
  eddy current, 2-57
  iron-core, 2-51
  loaded secondary, 2-50
  losses, 2-57
  modulation, 6-77
  multiwinding, 2-55
  phase shift, 2-48
  power, 3-31
  power in, 2-54
  step-down, 2-52
Transformer *(continued)*
  step-up, 2-52
  tapped winding, 2-56
  turns ratio, 2-52
  unloaded secondary, 2-48
Transistor(s), 1-32, 5-1
  basing, 5-13
  biasing, 5-14, 5-31
  bipolar, 5-70
  construction, 5-13
  IGFET, 5-69
  MOSFET, 5-69
  n-channel MOSFET, 5-69
  N-P-N, 5-12, 5-16
  oscillators, 6-17
  p-channel MOSFET, 5-70
  P-N-P, 5-12, 5-14
  r-f amplifier neutralization, 6-49
  unijunction (UJT), 5-65
  unipolar, 5-70
Transit time, 3-123, 5-21, 6-41
Transmisison line(s), 4-76, 6-118
  characteristic impedance, 6-120, 6-121
  coaxial cable, 6-119
  coupling, 6-56
  current loop, 6-126
  current node, 6-126
  fields, 6-123
  impedance, 6-120
  impedance mismatch, 6-127
  line mismatch, 6-127
  open-circuited, 6-128
  open-end, 6-128
  open-wire line, 6-119
  resonant transmission line, 6-128, 6-129
  ribbon lead, 6-119
  section applications, 6-131
  section properties, 6-130
  short-circuited, 6-129
  standing waves, 6-127
  standing wave ratio (SWR), 6-127, 6-156
  surge impedance, 6-121
  terminated, 6-122
  termination, 6-122, 6-126
  twin lead, 6-119
  types, 6-119
  velocity of propagation, 6-125
  velocity propagation constant, 6-125
Transmitter(s), 3-129
  AM, 6-69, 6-74
  AM-CW, 6-92
  controls, 6-112
  control system, 6-115
  CW, 6-45, 6-67
  CW-AM, 6-92
  fundamental, 6-3
  metering, 6-59
  power supply, 6-108
  SSB, 6-107
Transmitting tubes, 6-4
  ratings, 6-8
Treble control, 4-29
TRF (tuned radio-frequency)
  amplifier, 6-45
  power amplifier, 6-46
  receiver, 4-8, 4-15
Triangle, 2-3
Trigonometry functions, table of, 2-135
Trimmer capacitor, 4-11
Triode, 3-12
  basic circuit, 3-14
Trivalence, 5-5
True power, 2-93
Tube(s)
  amplification factor, 3-19
  anode, 6-6
  basing, 3-28
  beam-power, 3-25
  cathode emitter, 6-4
  ceramic, 6-7
  constants, 3-19
  construction, 3-2
  control, 3-54
  control grid, 6-5
  curves, 3-8, 3-16—3-18, 3-23
  development of, 3-1
  diode, 3-5
  driving power, 6-5
  dynamic characteristics, 3-11, 3-57
  dynamic transfer characteristics, 3-61
  emission, 3-3
  emitter, 6-4
  external anode, 6-7
  gas-filled rectifier, 6-9
  keyer, 6-64
  klystron, 3-128
  lighthouse, 3-124
  magnetron, 3-126
  mercury-vapor rectifier diode, 6-9
  multigrid, 3-27
  multi-unit, 3-27
  output-signal power, 6-6
  pentode, 3-24
  planar, 3-124
  plate, 6-6
  plate current, 3-7
  plate power input, 6-6
  plate resistance, 3-9, 3-10, 3-19, 3-20
  plate voltage, 3-7, 3-8
  ratings, 6-8
  rectifier, 6-9
  reflex klystron, 3-128
  r-f excitation, 6-5
  space charge, 3-6
  static characteristics, 3-8
  transconductance, 3-21
  tetrode, 3-22

Tube(s) *(continued)*
  transmitting, 6-4
  triode, 3-12
  type designation, 3-28
  variable-mu, 3-26
  vacuum, 3-2
  xenon-filled rectifier diode, 6-9
Tuned circuits, 4-9
Tuned-plate tuned-grid (TPTG) oscillator, 6-18
Tuned radio frequency. *See* TRF
Tuning procedures, 6-61
Tunnel diode, 5-63
Turns ratio, 2-52
Twin lead, 4-76, 6-119

UHF (ultra-high frequency), 4-2
  oscillator, 3-123
UJT (Unijunction transistor), 5-65
UJT-controlled relay circuit, 5-66
UJT oscillator, 5-66
Ultra-high frequency (UHF), 4-2
  oscillator, 3-123
Ultraudion oscillator, 3-121
Unijunction transistor (UJT), 5-65
Unilateralization, 6-49
Unipolar transistor, 5-70
Universal time constant chart, 2-98
Upper sideband, 6-72

Vacuum tubes, 3-2
Valley current, 5-63
Valley voltage, 5-63
Valve, 3-1
V-antenna, 6-154
Varactor diode, 4-113
  AFC, 4-113
Variable capacitors, 2-77, 4-11
Variable-frequency oscillator (VFO), 6-28
Variable-mu, 3-26
Variable reactance, 4-110
Varistor, 1-64
Vector(s), 2-4, 2-5
  component, 2-6
Vector(s) *(continued)*
  direction, 2-4
  magnitude, 2-4
  multiple, 2-5
  in parallel R-L circuit, 2-43
  reference, 2-6
  in series L-C-R circuit, 2-107
  in series R-C circuit, 2-86
  in series R-L circuit, 2-41
Velocity, 6-134
Velocity microphone, 6-83
Velocity of propagation, 6-125
Velocity propagation constant, 6-125
Vertex, 2-2
Vertical antenna, 6-151
Vertical polarization, 6-133
Vertical radiation, 6-136
Very high frequency (VHF), 4-2
Very low frequency (VLF), 4-2
VFO (variable-frequency oscillator), 6-28
VHF (very high frequency), 4-2
Virtual cathode, 3-25
VLF (very low frequency), 4-2
Voice coil, 3-101, 3-105
Volt, 1-34
Voltage
  alternating, 2-1
  amplification, 3-66
  amplifier, 3-56, 3-75
  A-type, 3-12
  bias, 6-58
  breakdown, 5-62
  B-type, 3-12
  C-type, 3-12, 3-20
  distribution. *See* Voltage distribution
  divider, 1-82, 1-86, 3-43
  doubler, 3-47, 3-48
  drop, 1-82, 1-84
  effective value, 2-17
  feedback, 3-104
  gain, 3-66, 3-84, 5-19, 5-34
  generation of, 2-8
  negative, 3-44
  Ohm's Law for finding, 1-68
  output, 1-34
Voltage *(continued)*
  quadrupler, 3-49
  regulators, 3-51—3-54, 3-58, 5-62
Voltage distribution
  in parallel R-L circuit, 2-42
  in series L-C-R circuit, 2-107
  in series R-C circuit, 2-86
  in series R-L circuit, 2-41
Voltage-plate current curves, 3-8
Voltmeter, 1-49, 1-75, 1-128
Volume control, 4-13, 4-30

Watt, 1-70
  James, 1-70
Watt hour, 1-73
Wattmeter, 1-36, 1-75
Waveform, 2-12
Wavefront, 6-135
Wavelength, 6-124, 6-125, 6-134, 6-142
Wave propagation, 6-136
Wave trap, 4-6
Weber, 1-106
Wheatstone bridge, 1-137
Winding
  non-inductive, 2-26
  pie, 6-44
Wire gauge, 1-61, 1-139
Wire-wound resistor, 1-62

X-cut crystal, 6-20
Xenon-filled rectifier diode, 6-9

Yagi antenna, 6-148
Y-cut crystal, 6-20

Zener breakdown voltage, 5-10
Zener diode, 3-53, 5-62
  voltage regulator, 5-62
Zener voltage, 5-62
Zero beat, 4-47
Zinc-carbon cell, 1-41, 5-57
Zinc chloride, 1-42
Zinc-mercury oxide cell, 1-43

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